GPDs at an Electron Ion Collider

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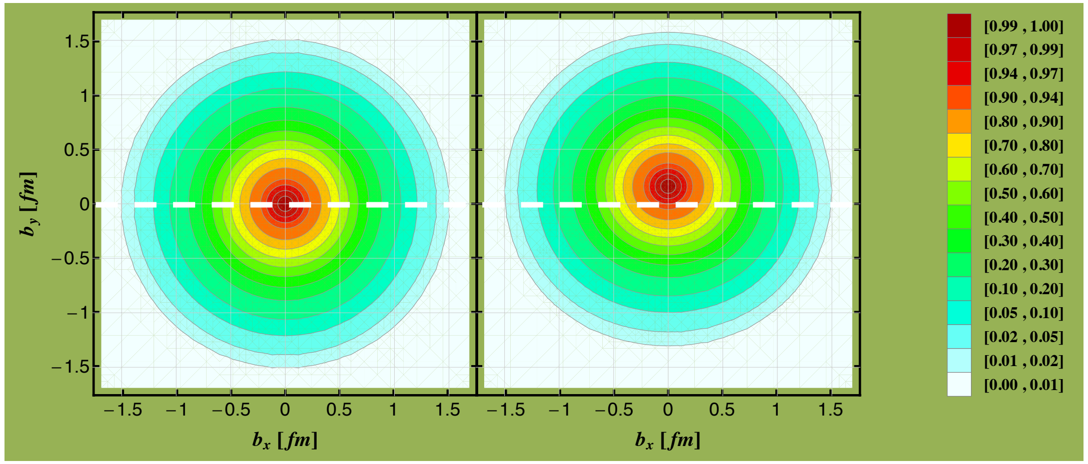
(for the BNL EIC Science Task Force)



DIFFRACTION 2012

Puerto del Carmen, Lanzarote – Canary Islands

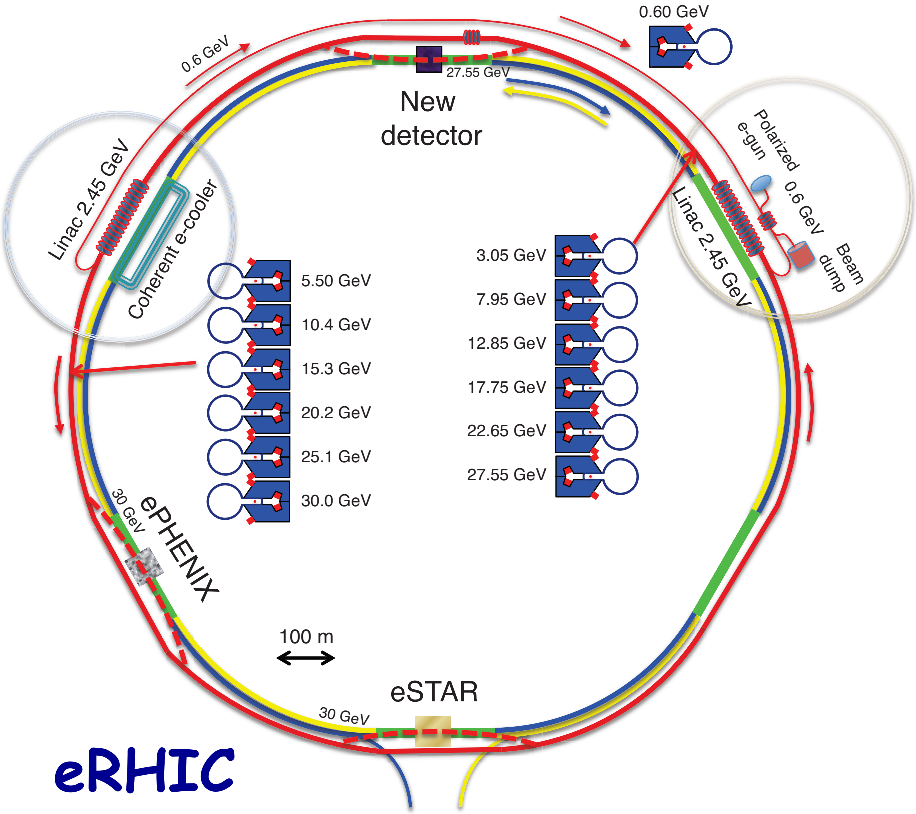
September 10-15, 2012

The EIC project

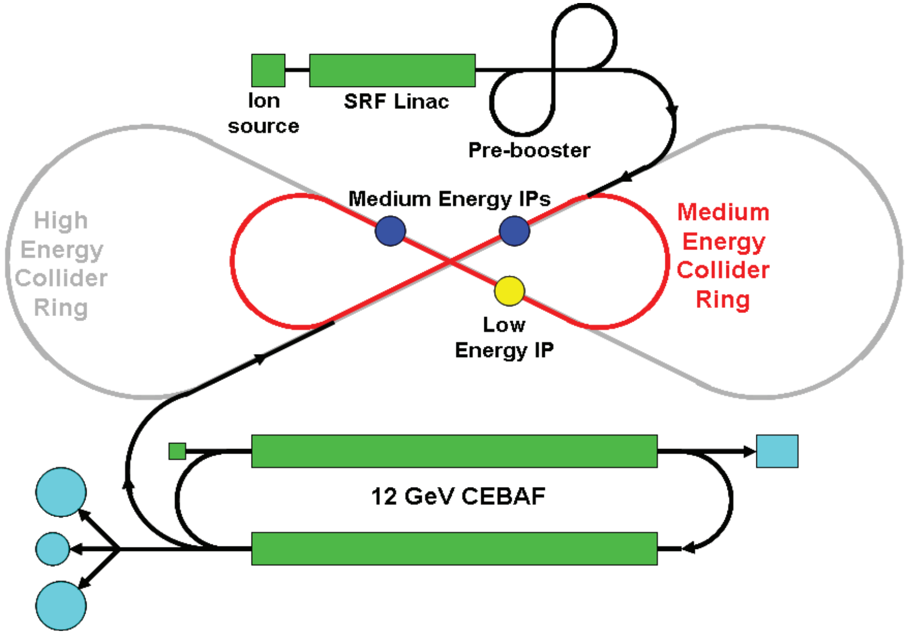
Electron Ion Collider project (EIC) -> 2 options:

Brookhaven National Laboratory (eRHIC)

Thomas Jefferson National Laboratory (ELIC)



eRHIC



ELIC

Center mass energy range: $\sqrt{s}$=28-200 GeV

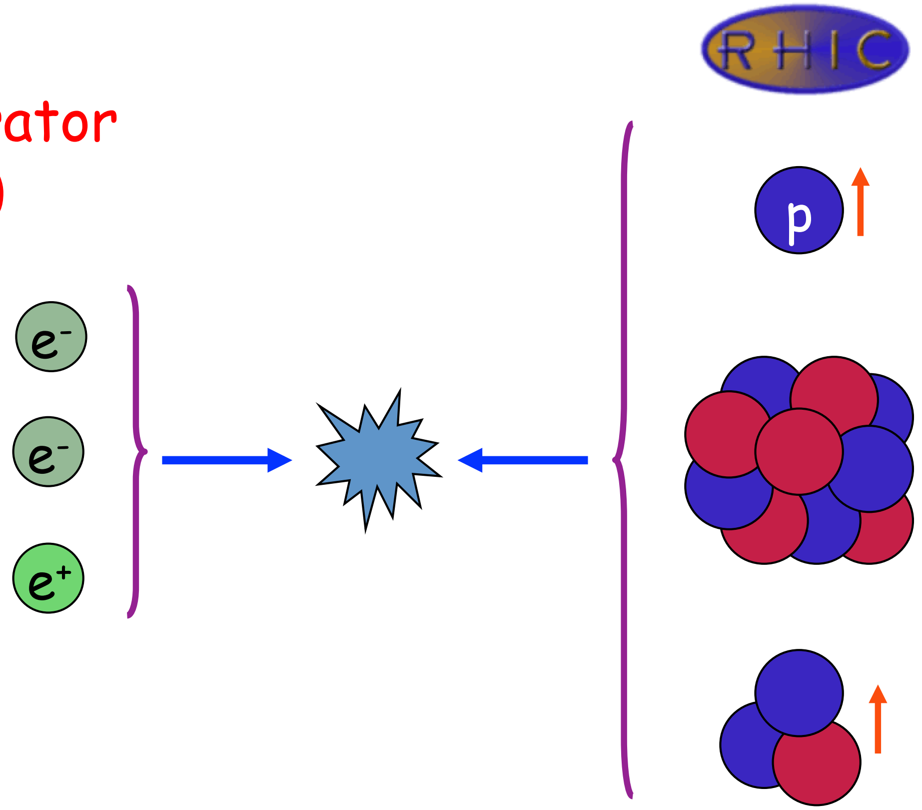
High beam polarization for both hadrons and electrons

Mission: Studying the Physics of Strong Color Fields

The eRHIC idea

Electron accelerator
(to be build)

Unpolarized and
polarized leptons
5-20 (30) GeV



(Existing)

Polarized protons
75-250 (325) GeV

Light ions (d,Si,Cu)
Heavy ions (Au,U)
50-100 (130) GeV/u

Polarized light ions
(He^3) 215 GeV/u

Center mass energy range: $\sqrt{s}$=28-200 GeV

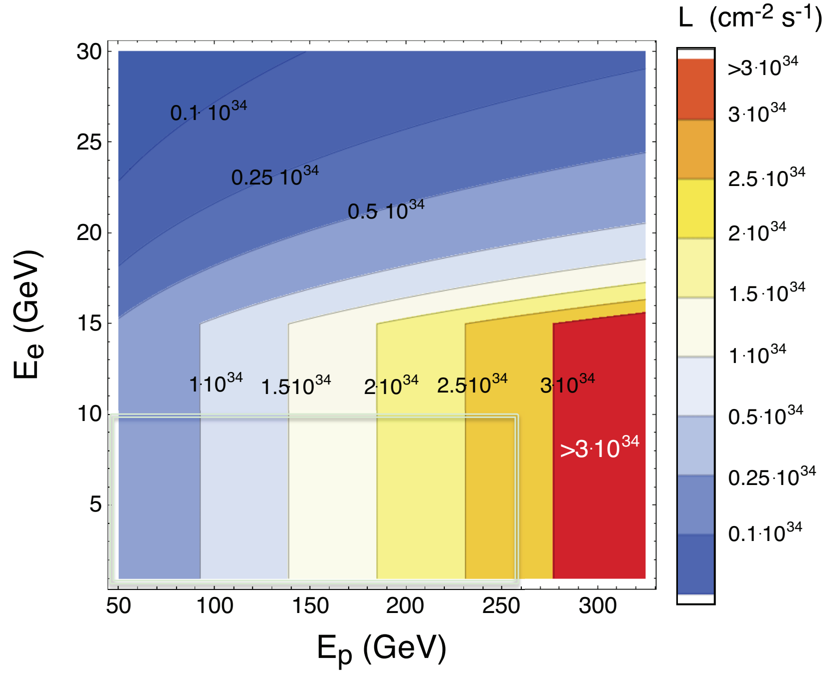
EIC/eRHIC – experimental features

Why EIC is unique:

- ❑ 5 - 30 GeV electrons on 75-250 GeV (50-100GeV) protons (nuclei). Polarization of electrons and protons (nuclei)
- ❑ Lumi: ~10^{34} $cm^{-2}s^{-1}$

Important for exclusive DIS:

- Dedicated forward instrumentation
- High tracker coverage
- Very High lumi!



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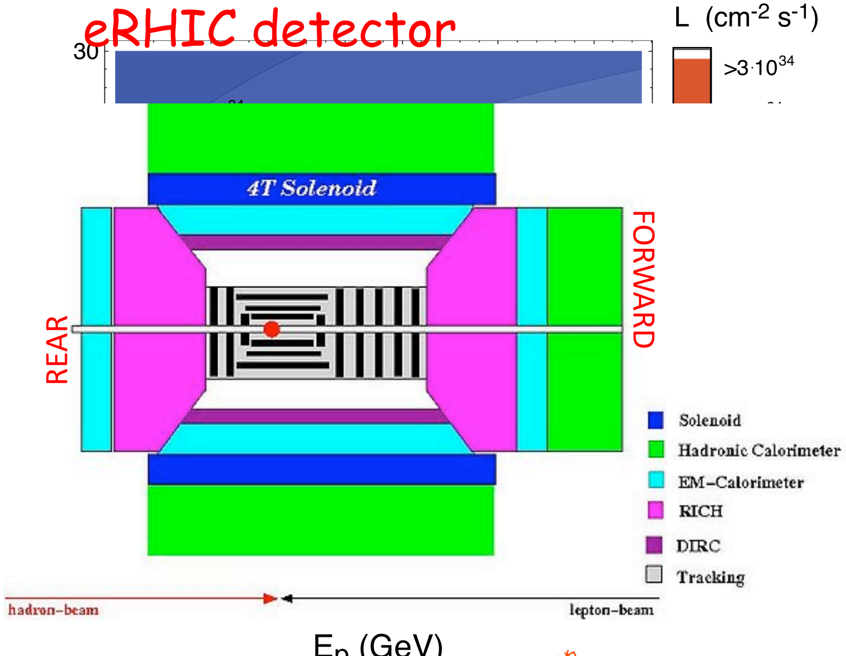
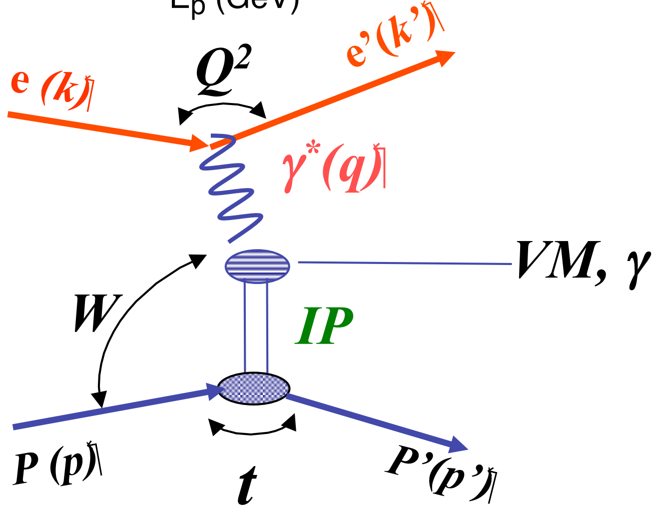
eRHIC detector



What are the detector requirements:

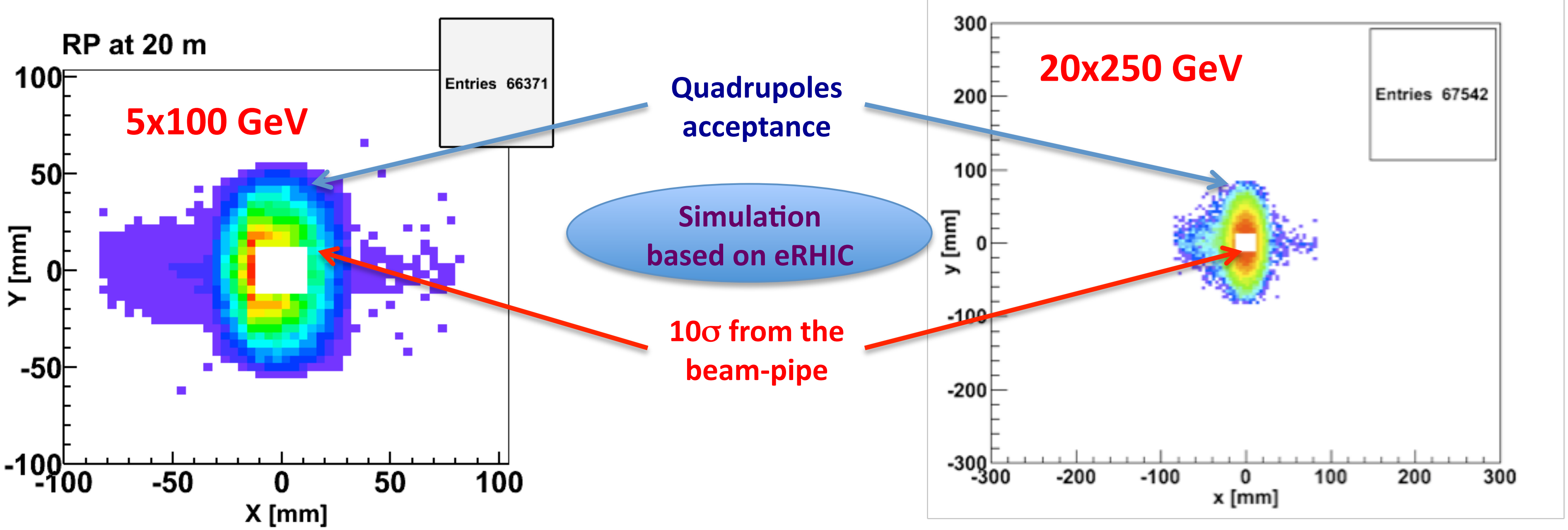
Important for exclusive diffraction:

- Hermetic Central Tracking Detector
- Good EM calorimeter resolution with fine granularity
- Preshower em cal → π^0 background
- Very forward calorimetry
- **Roman pots (and with excellent acceptance)**



Direct |t| measurement – Roman Pots

Accepted in"Roman Pot"(example) at s=20m



- high-|t| acceptance mainly limited by magnet aperture
- low-|t| acceptance limited by beam envelop (~10σ)
- |t|-resolution limited by
  - beam angular divergence ~100μrad for small |t|
  - uncertainties in vertex (x,y,z) and transport
  - ~<5-10% resolution in t (RP at STAR)

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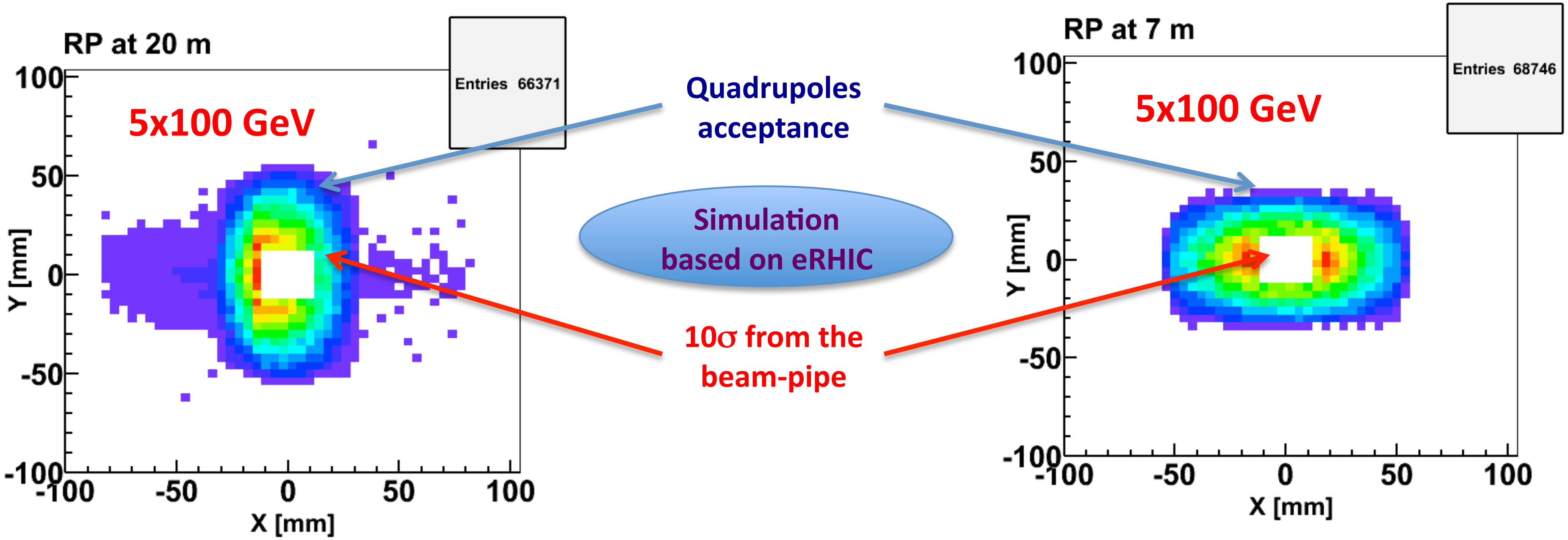

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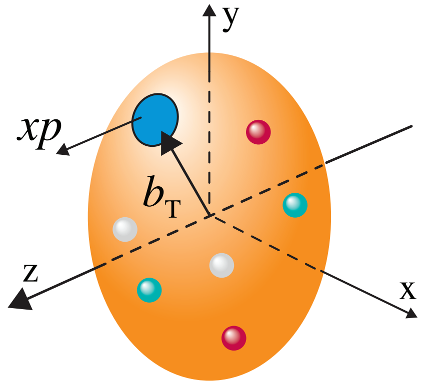
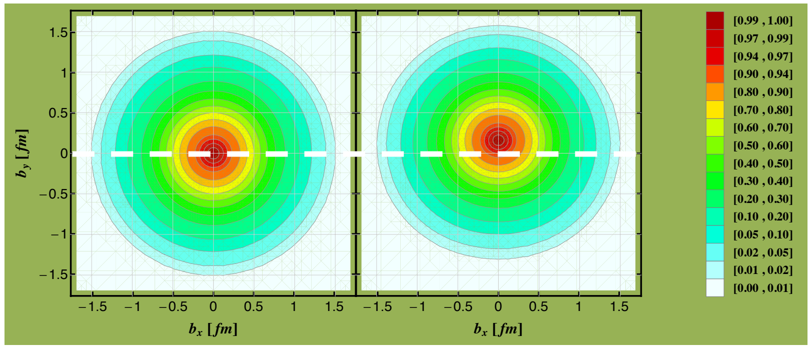
(2+1)-Dimensional imaging of the proton

Open questions:

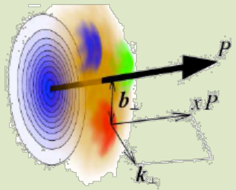
- **PDFs do not resolve transverse coordinate or momentum space**
- **In a fast moving nucleon the longitudinal size squeezes like a `pizza' but transverse size remains about 1 fm**



Goal: nucleon tomography!



Proton imaging

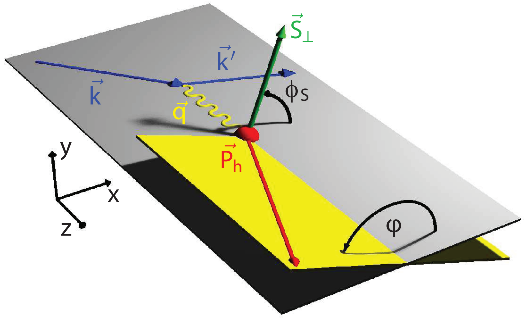


- what is the spatial distribution of quarks and gluons in nucleons/nuclei
- Possible window to orbital angular momentum

Accessing the GPDs

$$\frac{d\sigma}{dt} \sim A_0 \left[|H|^2(x,t,Q^2) - \frac{t}{4M_p^2} |E^2|(x,t,Q^2) \right]$$

Dominated by H
slightly dependent on E

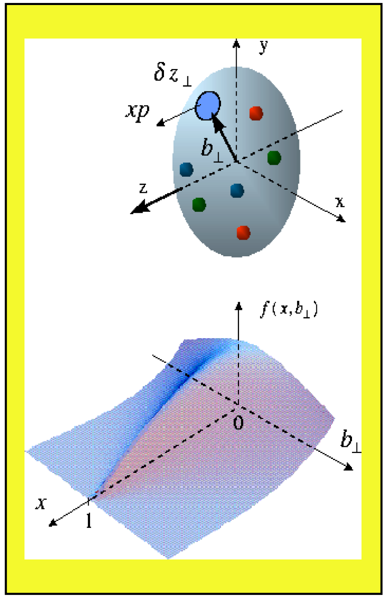


$$\varphi = \phi_h - \phi_l$$

Angle btw the production and scattering planes

$$\varphi_s = \Phi_T - \phi_h$$

Angle btw the scattering plane and the transverse pol. vector



$$A_C = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \propto Re(A)$$

→ **Requires a positron beam at eRHIC**

$$A_{LU} \propto y \left[F_1(t) H(\xi,\xi,t,Q^2) - \frac{t}{4M^2} F_2(t) E(\xi,\xi,t,Q^2) + \ldots \right]$$

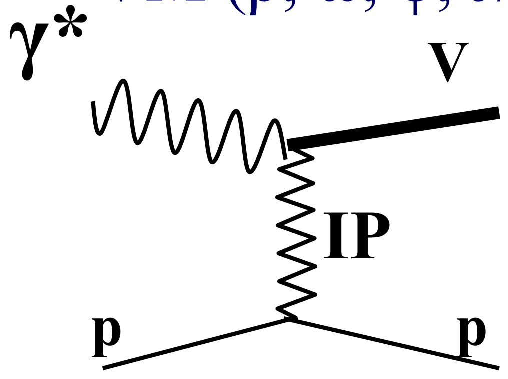
Dominated by H
slightly dependent on E

$$A_{UT} \propto \sqrt{\frac{-t}{4M^2}} \left[F_2(t) H(\xi,\xi,t,Q^2) - F_1(t) E(\xi,\xi,t,Q^2) + \ldots \right]$$

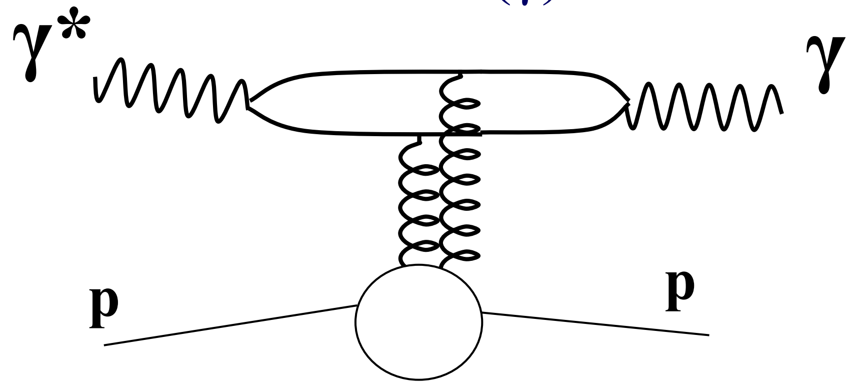
sin($\Phi_T - \phi_N$)
governed by E and H

Deeply Virtual Compton Scattering

VM (ρ, ω, φ, J/ψ, Y)



DVCS (γ)

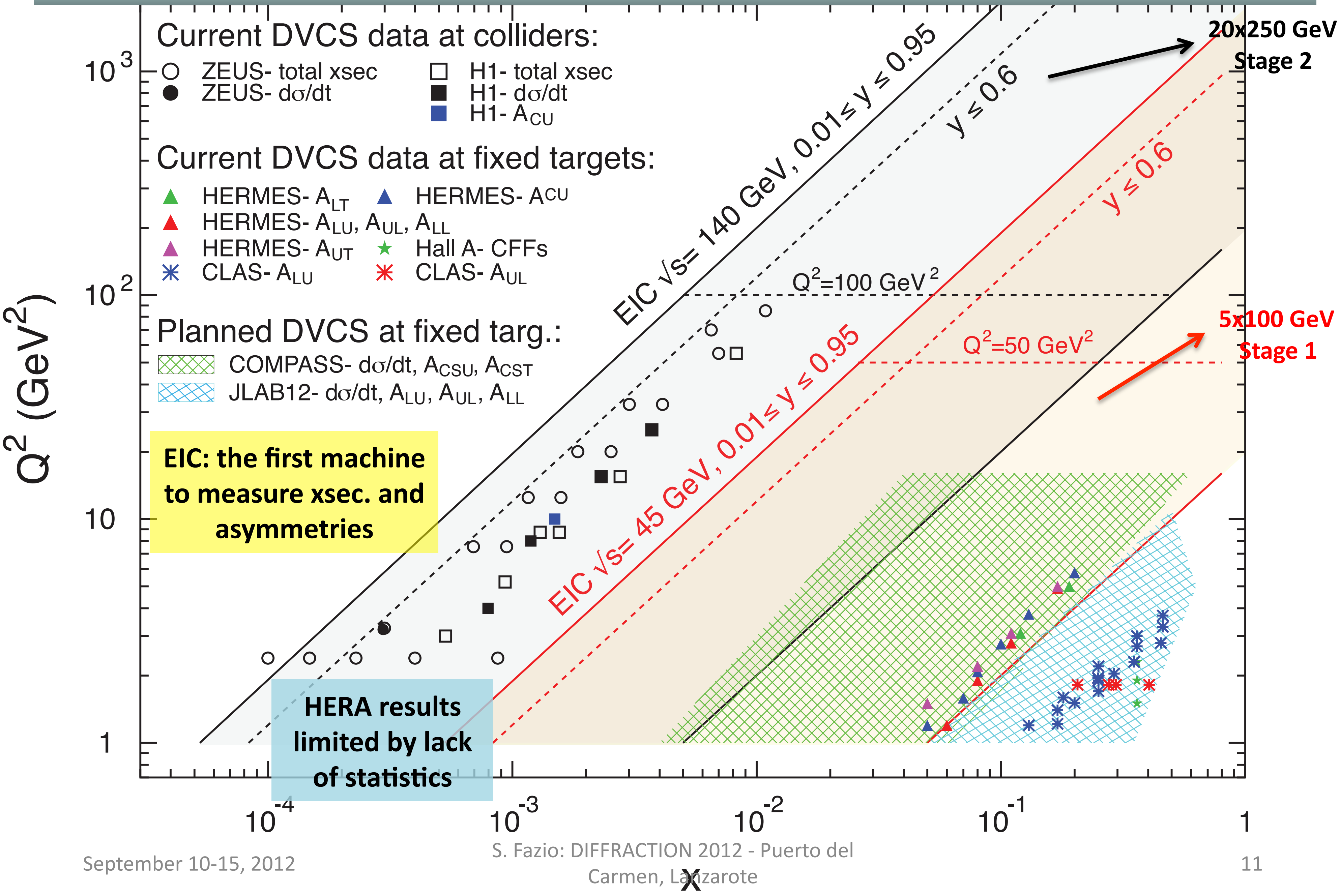


Scale: $Q^2 + M^2$ ⟷ Q^2

DVCS properties:

- **Similar to VM production, but γ instead of VM in the final state**
- **Very clean experimental signature**
- **Not affected by VM wave-function uncertainty**
- **Hard scale provided by Q^2**
- **Sensitive to both quarks and gluons (via evolution)**

DVCS phase-space



Scanning the phase space…

EIC lumi:
~10 fb^{-1}/year @ stage 1 – 5x100
~100 fb^{-1}/year @ stage 2 – 20x250

Acceptance criteria

- for Roman pots: $0.03 < |t| < 1.5$ GeV^2
- $0.01 < y < 0.85$
- $\eta < 5$

➢ BH rejection criteria (applied to x-sec. measurements)

- $y < 0.6$
- $(\theta_{el}-\theta_{\gamma}) > 0$
- $E_{el} > 1$GeV^2; $E_{\gamma} > 1$GeV^2

➢ Events smeared for expected resolution in t, Q^2, x

➢ Systematic uncertainty assumed to be ~5%

➢ Overall systematic uncertainty from luminosity measurement not taken into account

Scanning the phase space…

EIC lumi:
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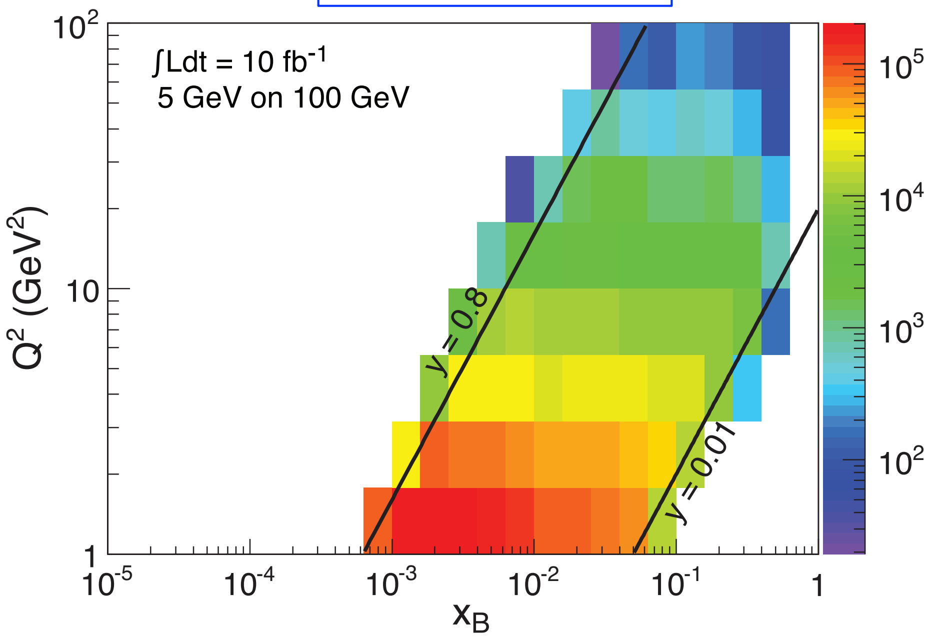
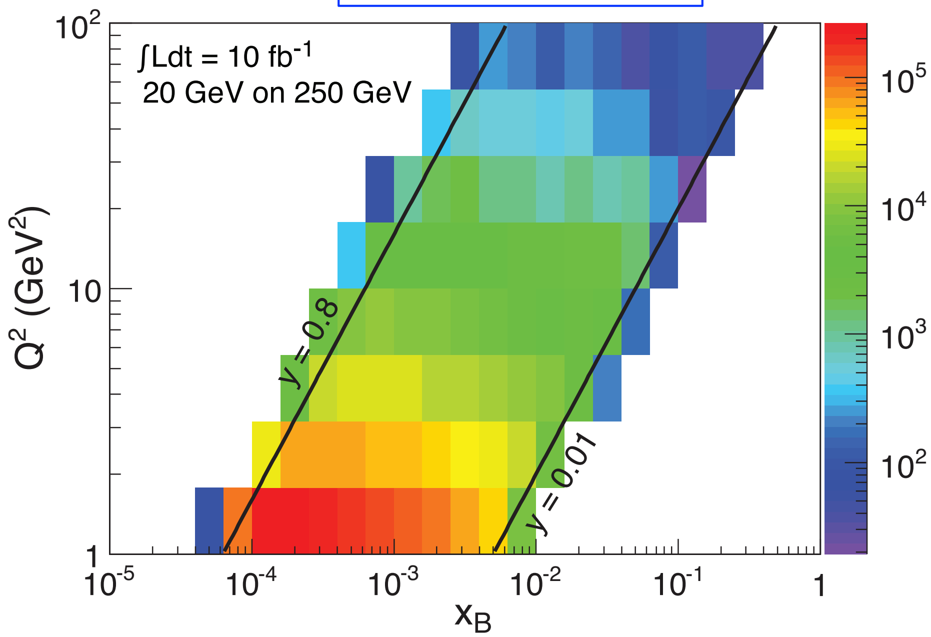
- **EIC will provide sufficient lumi to bin in multi-dimensions**
- **wide x and Q^2 range needed to extract GPDs**

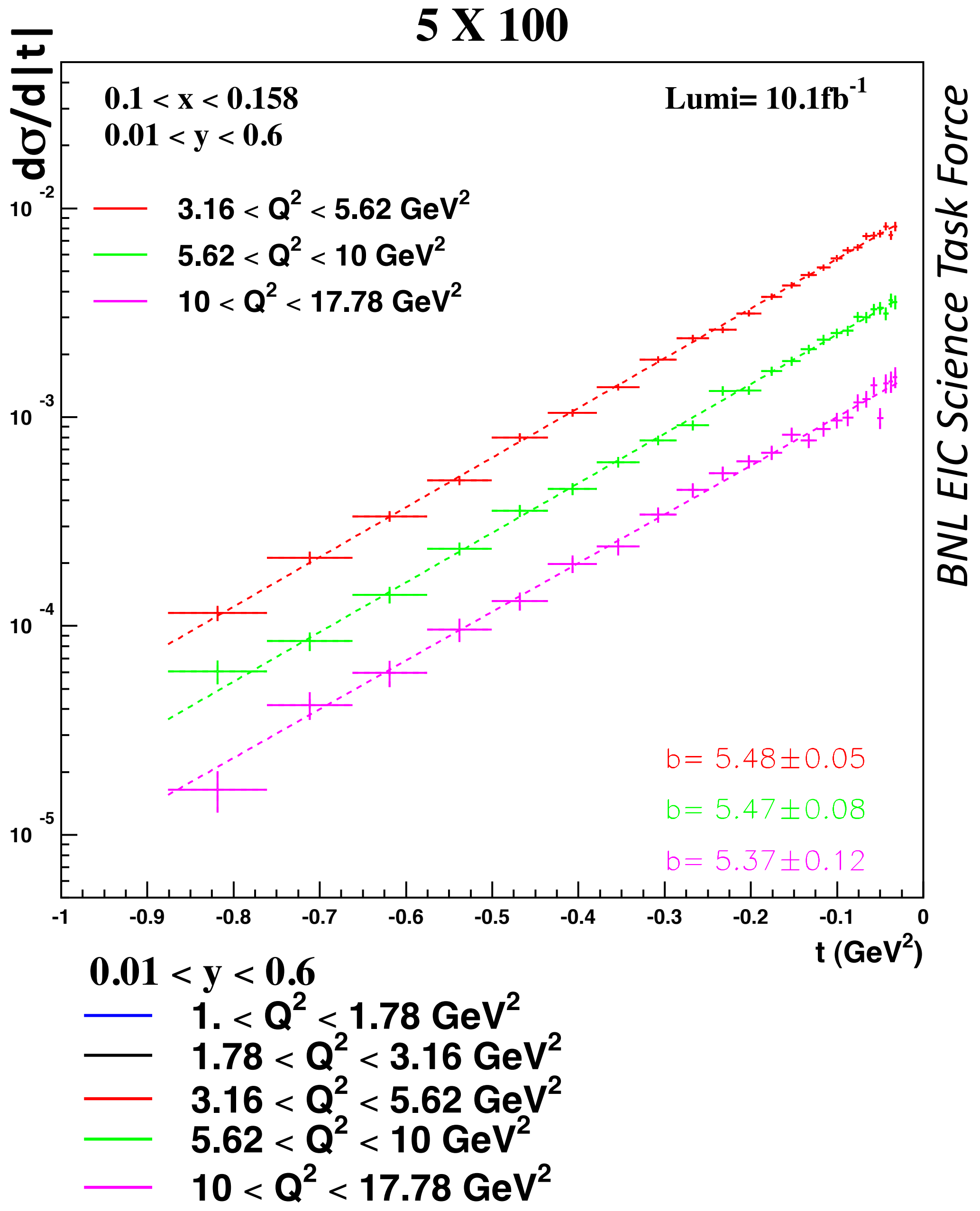
5 X 100 – stage 1



20 X 250 – stage 2



… we can do a fine binning in Q2 and W… and even in |t|



dσ/d|t|

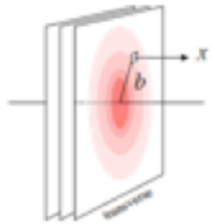
$$\frac{d\sigma}{d|t|} = \frac{\# evt}{\Delta_{bin} \bullet A \bullet \mathcal{L}} \quad \sim e^{-bt}$$

b=5.6

|t|-differential cross section is a very powerful tool

- **Gives precise access to GPD H**
- **Fourier transform -> direct imaging in impact parameter space**

$$q(x,b^2) \approx \int dt e^{-ibt} \frac{d\sigma}{dt}$$



- **|t|-binning –> 3 * resolution (or higher)**
- **Statistical error down to 1%**

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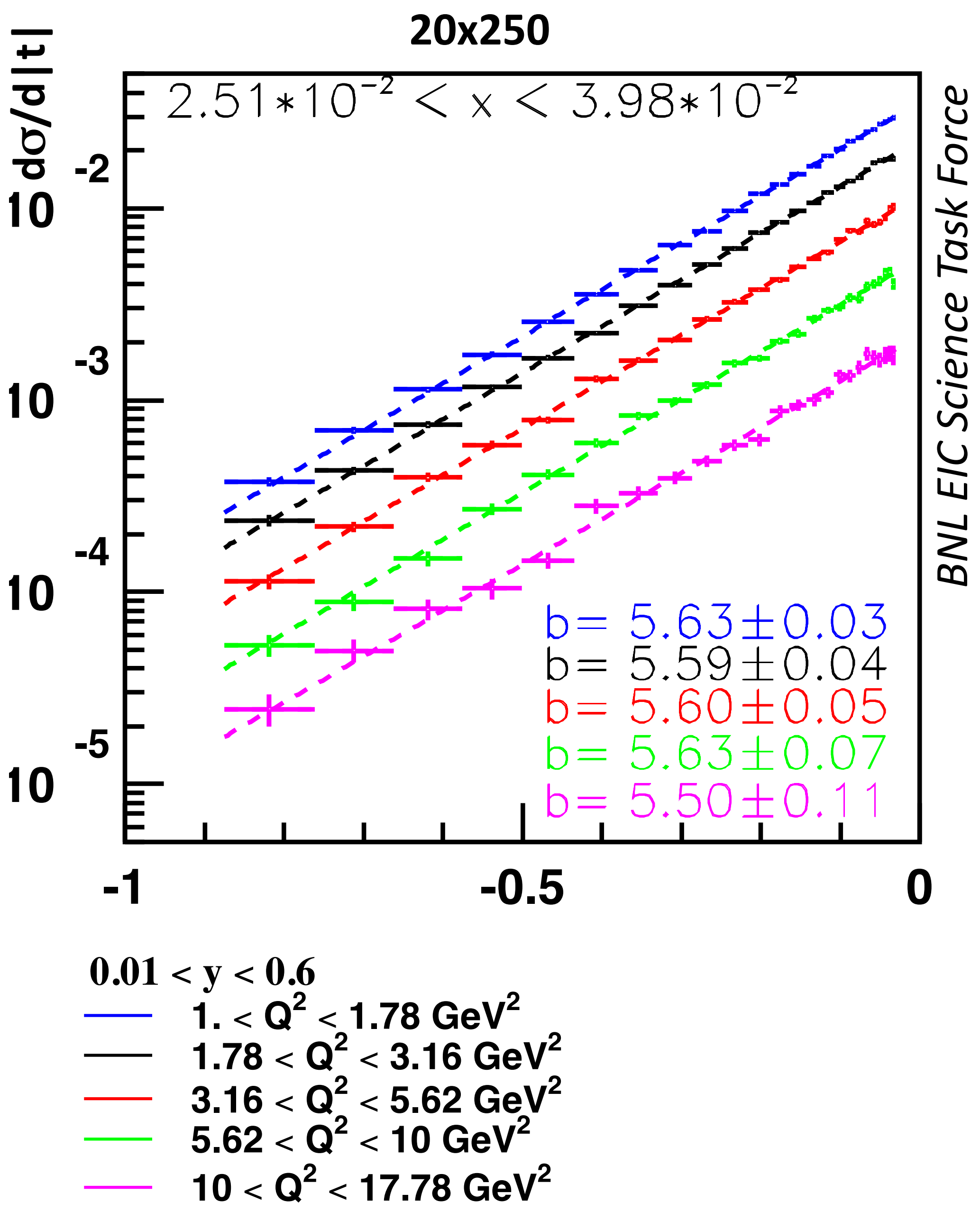

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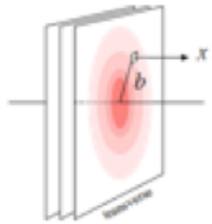

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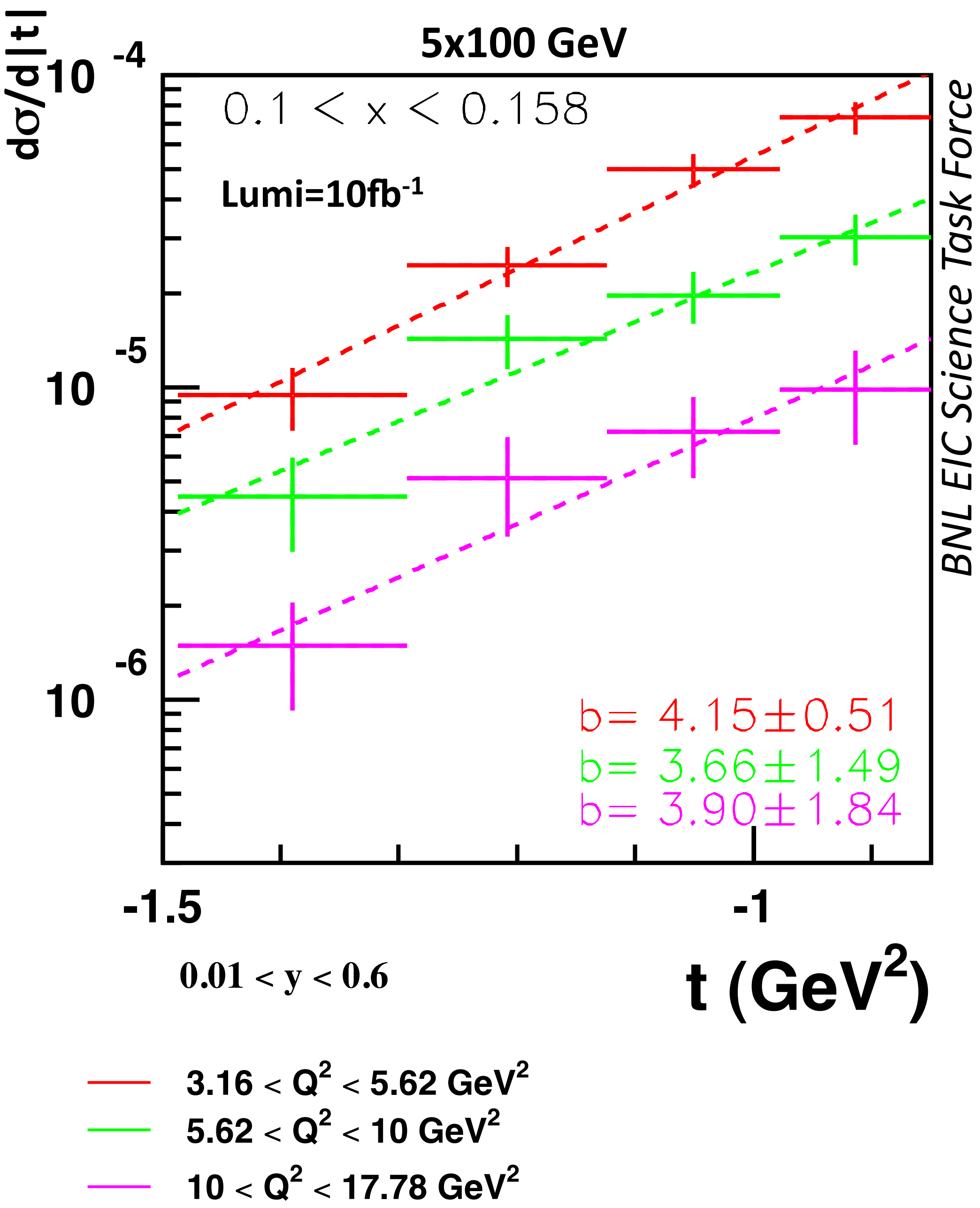

dσ/d|t| - large |t|

EIC lumi:
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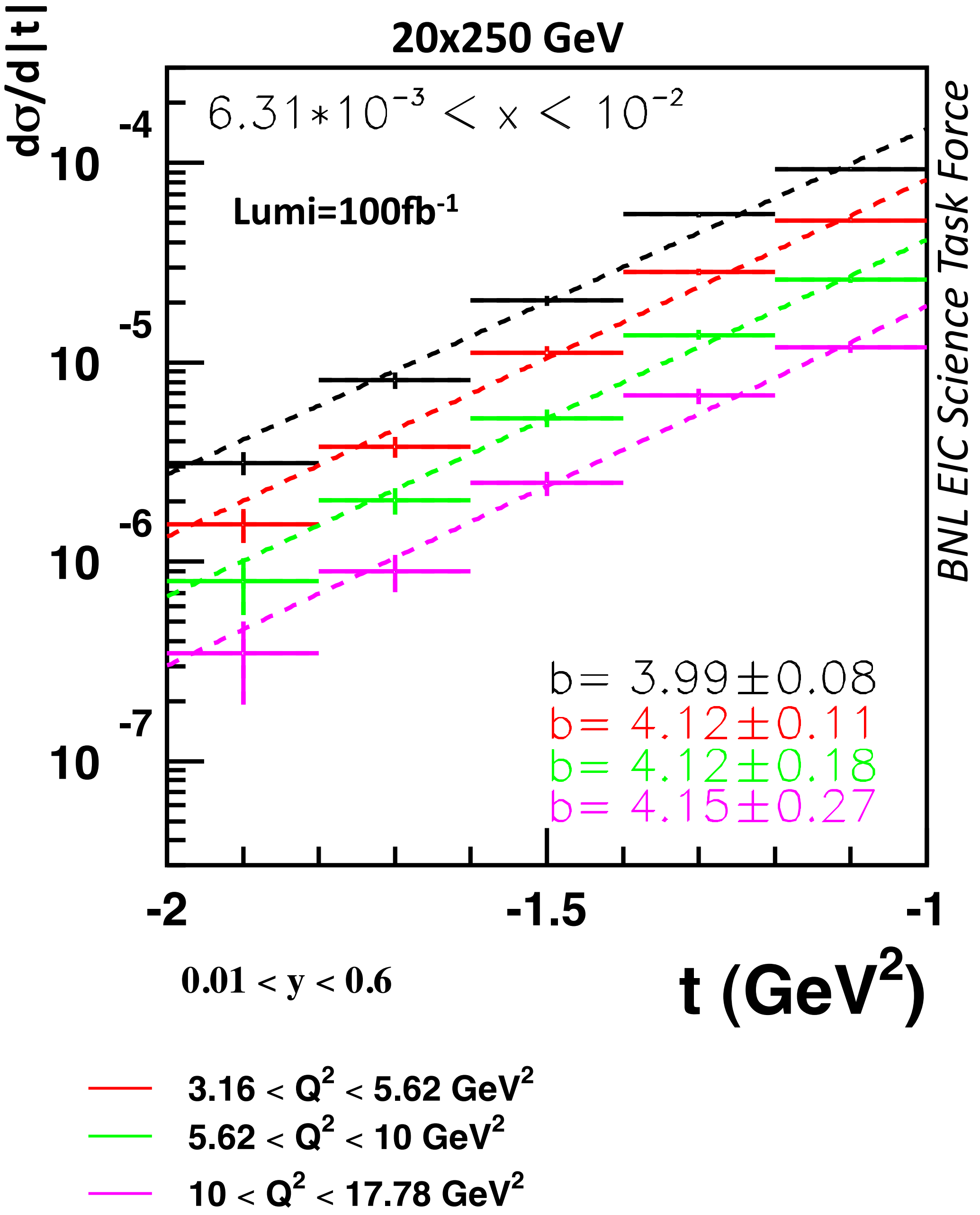
Dependence at large-|t| still unknown

Measurements possible also at large-|t| with a sufficient precision

Very important to constrain GPDs

$$\frac{d\sigma}{dt} \propto \mathrm{Im}(A) \rightarrow GPD\ H$$



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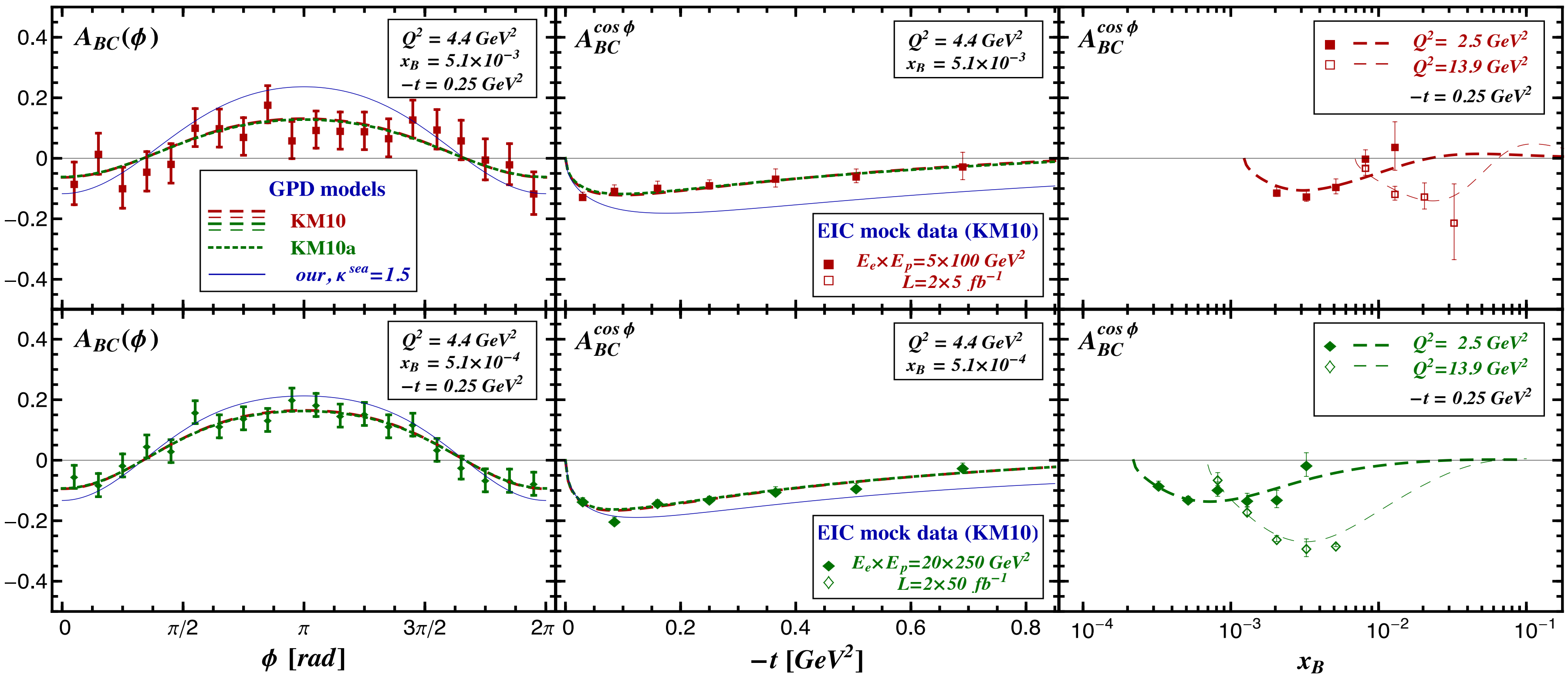
Asymmetries

Unpolarized positron beam → beam charge asymmetry (Ac)

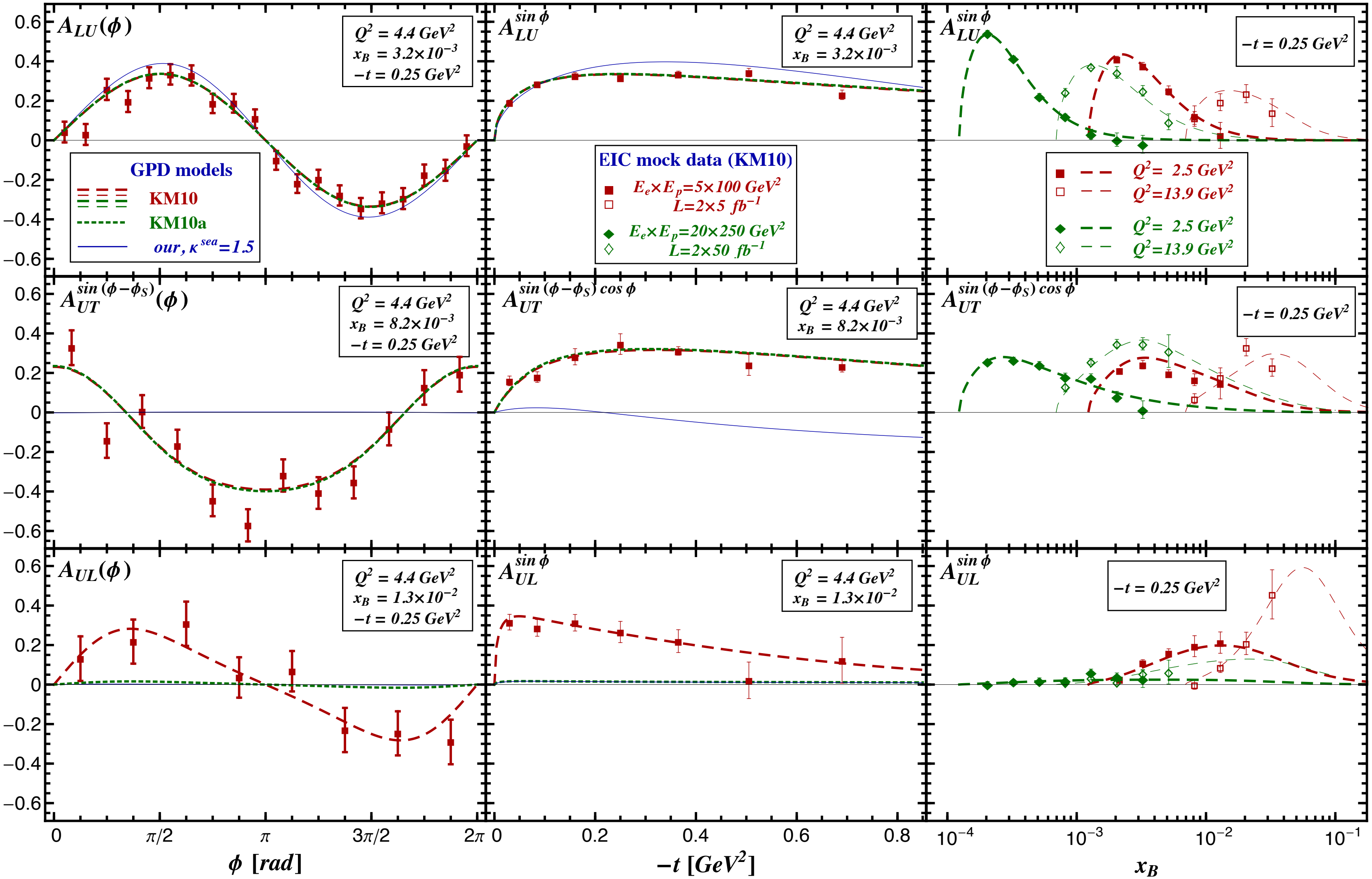


$$A_C \propto Re(A)$$

The complex Amplitude can be accessed

Asymmetries

Beam long. and transverse polarization → beam helicity asymmetries (A_{UL}, A_{LU}, A_{UT})

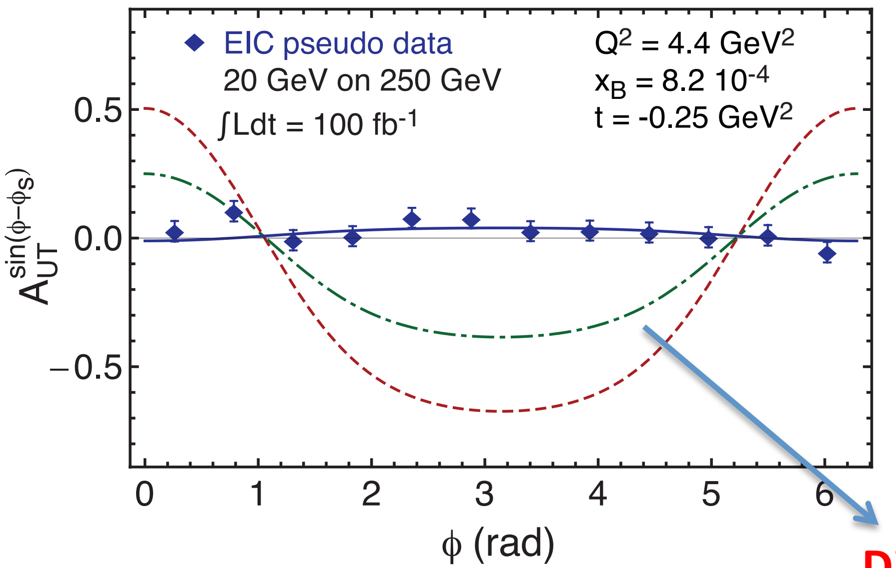


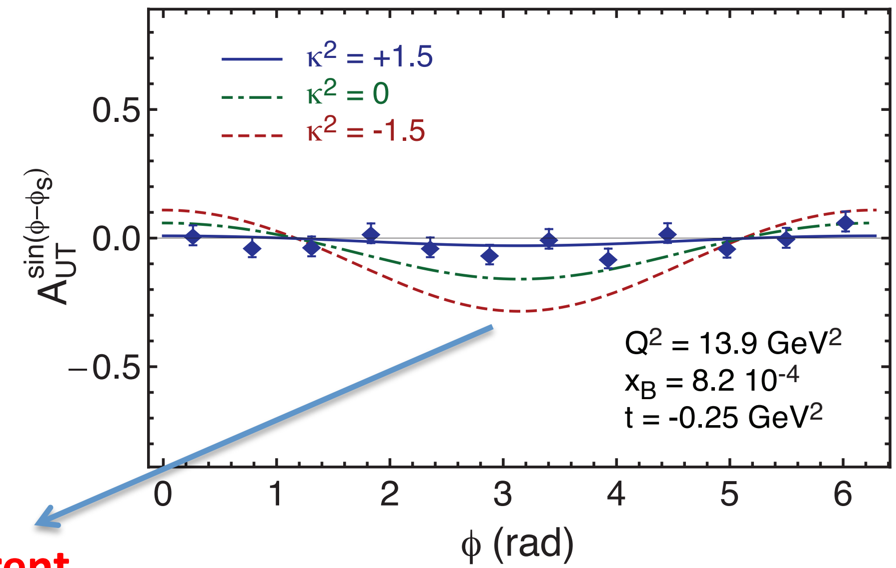
→ GPD H

→ GPD E

→ GPD H̃

Transverse target-spin asymmetry





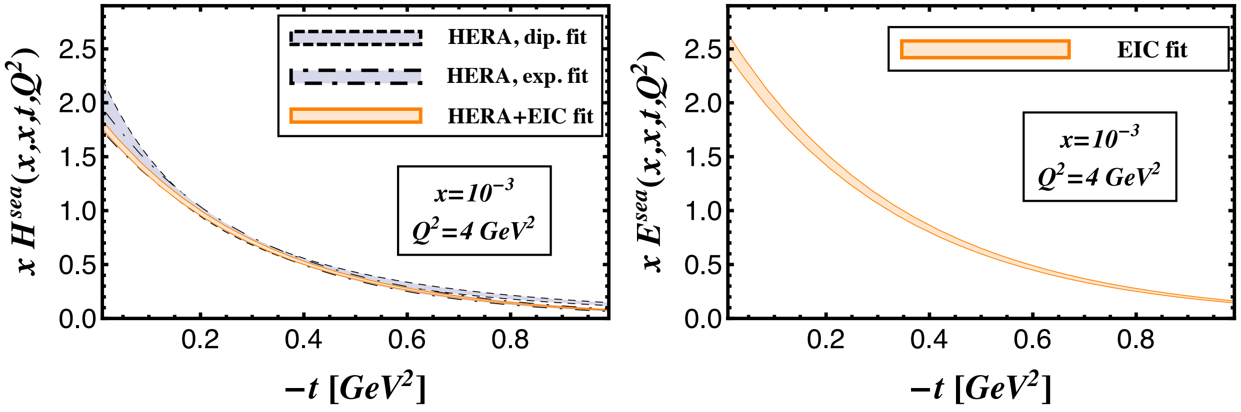
Different assumptions for E

$$A_{UT} \propto \sqrt{\frac{-t}{4M^2}}\left[F_2(t)H\left(\xi,\xi,t,Q^2\right) - F_1(t)E\left(\xi,\xi,t,Q^2\right) + \ldots\right]$$

$\sin(\Phi_T - \phi_N)$
governed by E and H

Gives access to GPD E

Imaging



$$q\left(x,\vec{b},\mu^2\right) = \frac{1}{4\pi}\int_0^\infty d|t|\,J_0\left(|\vec{b}|\sqrt{|t|}\right)H\left(x,\eta=0,t,\mu^2\right)$$

- A global fit over all mock data was done, based on the GPDs-based model: [K. Kumerički, D Müller, K. Passek-Kumerički 2007]
- Known values *q(x)*, *g(x)* are assumed for H^q, H^g (at t=0 forward limits E^q, E^g are unknown)

Impact of eRHIC:

- ✓ Excellent reconstruction of H^{sea}, and H^g (from $d\sigma/dt$)
- ✓ Reconstruction of GPD E (connection to the orbital momentum g-sum role)

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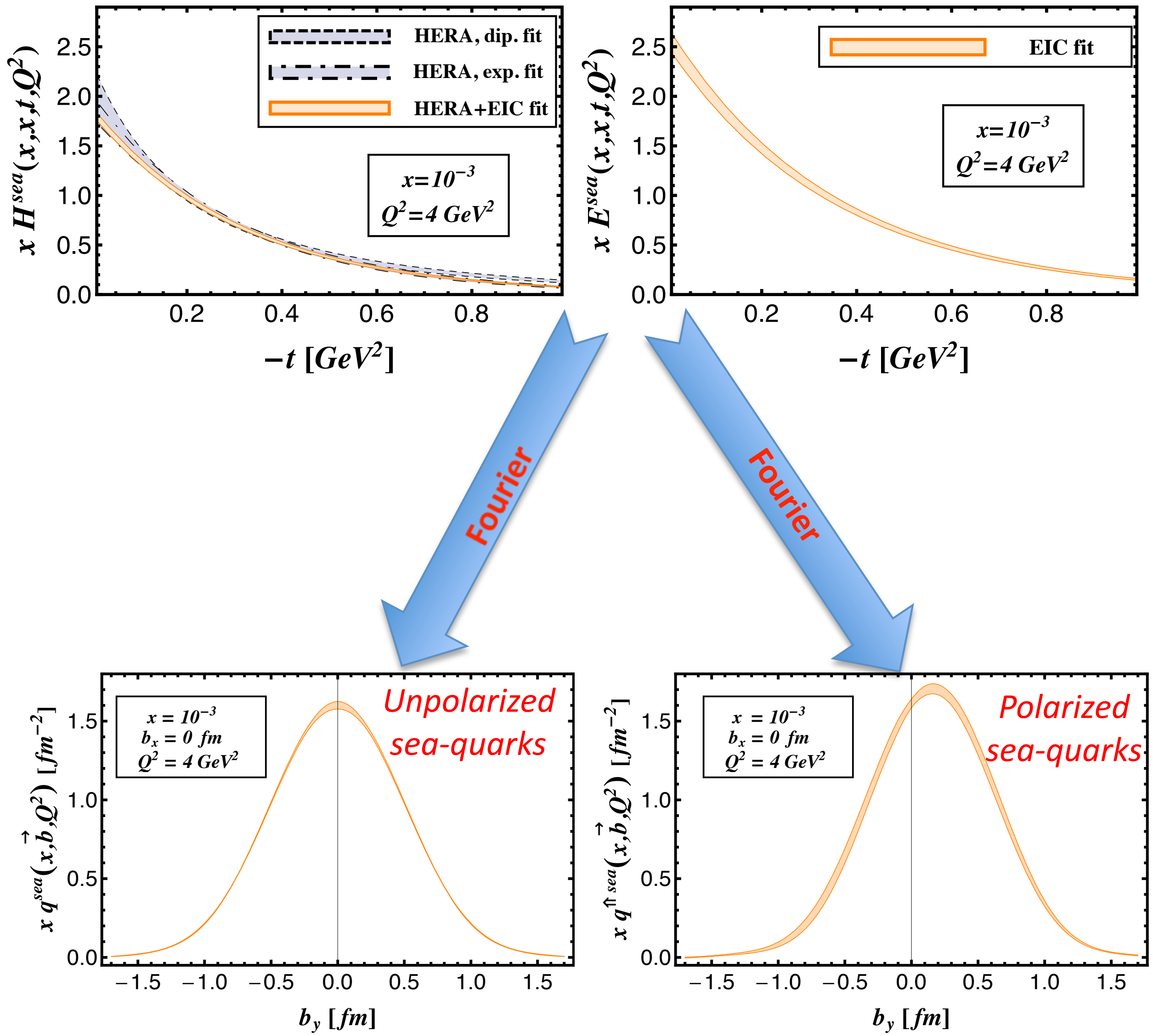

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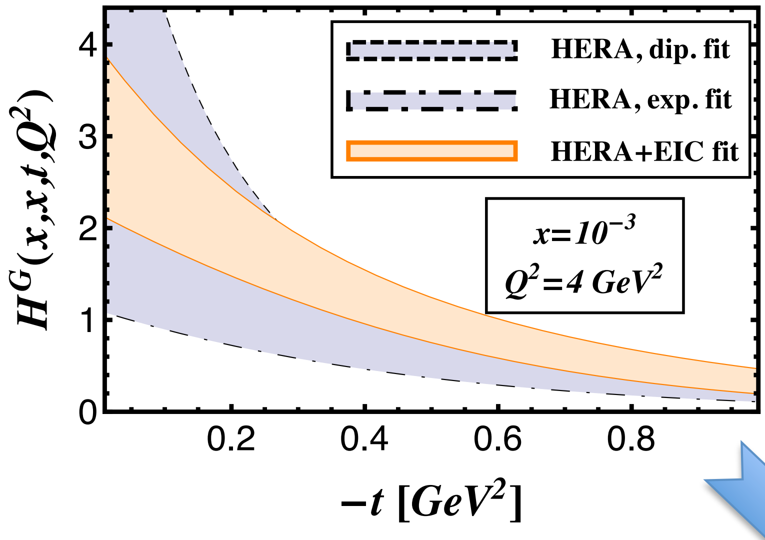

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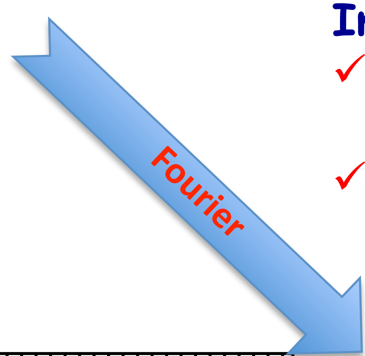

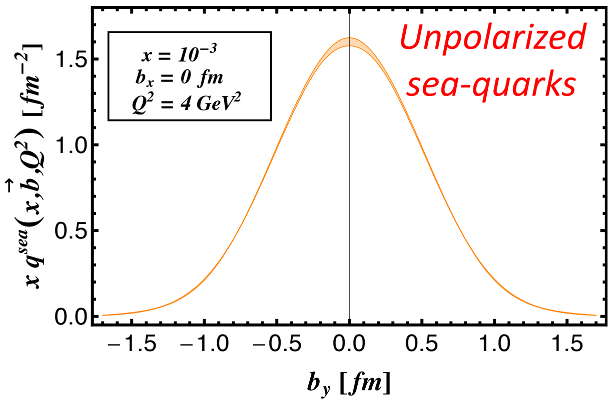

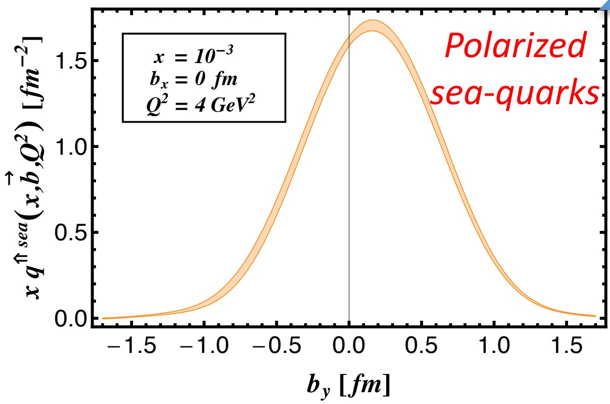

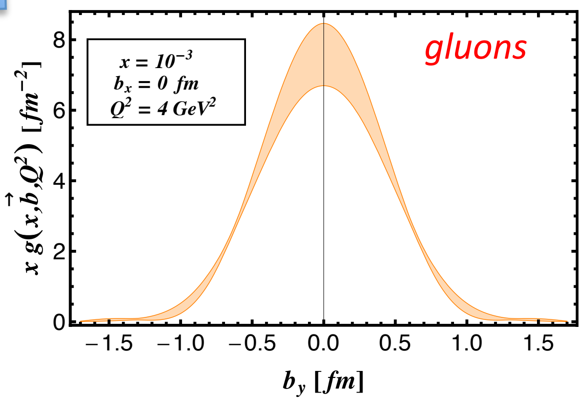

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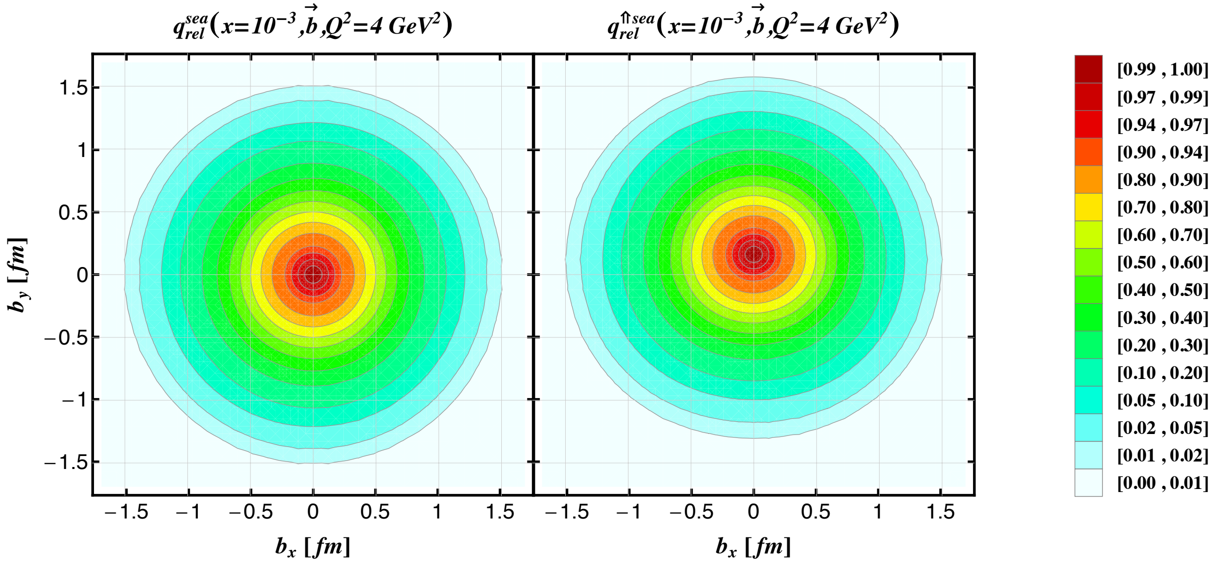

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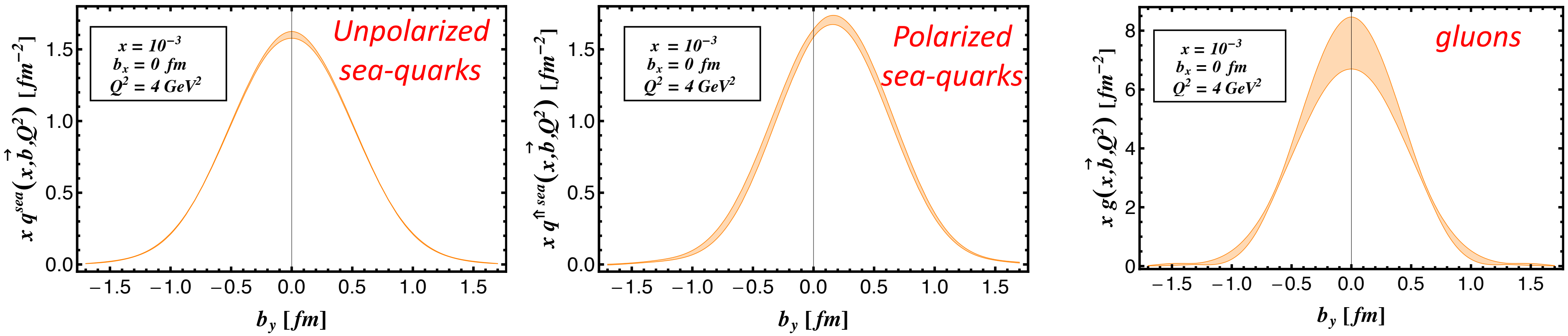

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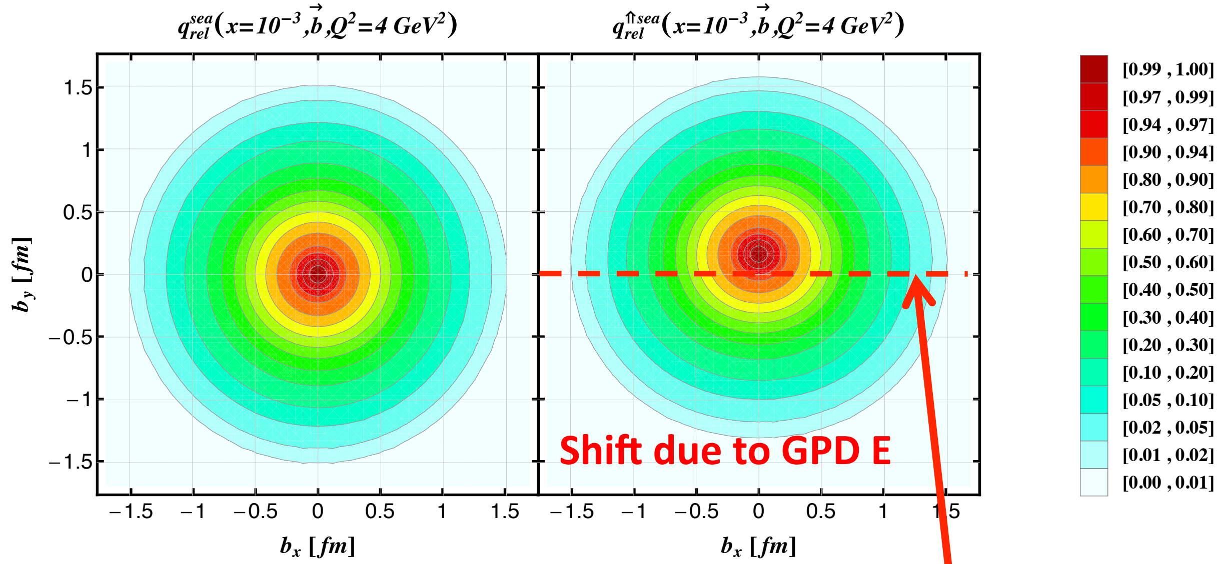

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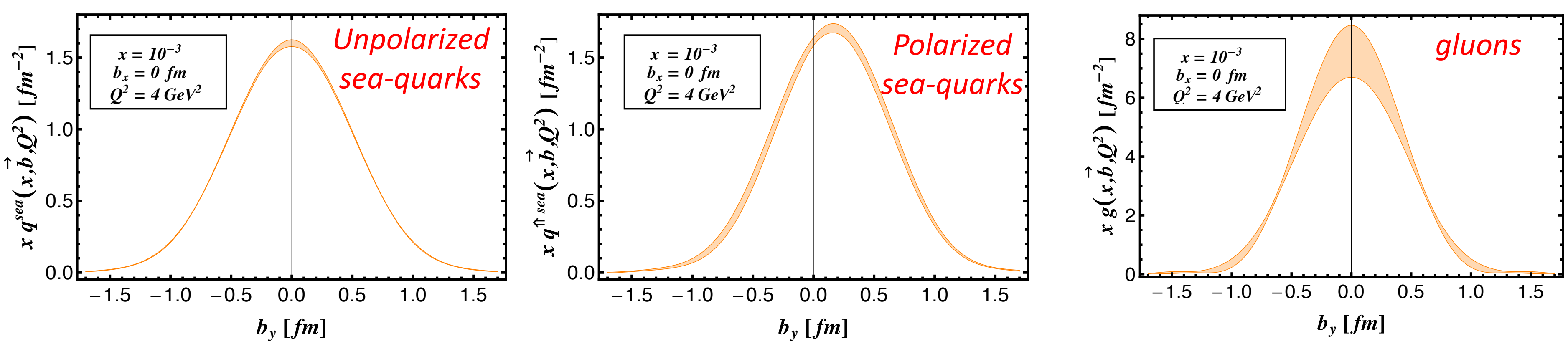


All details and more to appear in:

Deeply Virtual Compton Scattering at a proposed high-luminosity Electron-Ion-Collider

E. Aschenauer[1], *S. Fazio*[1], *K. Kumerički*[2], *D. Müller*[1,3]

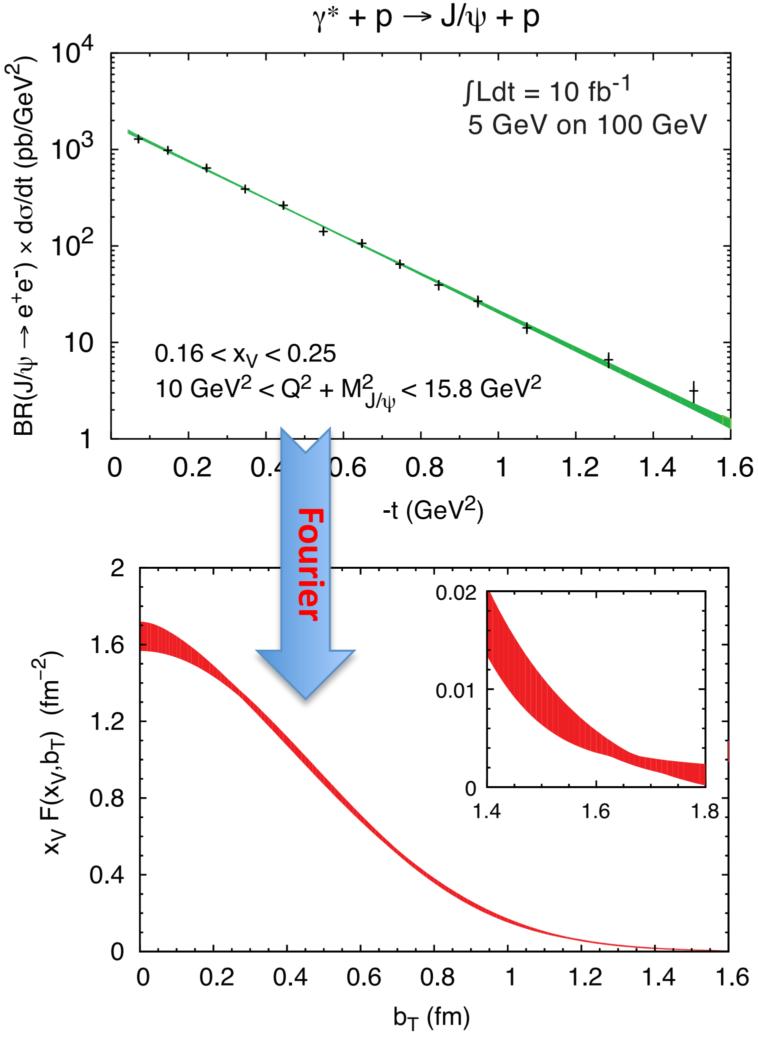
[1] *Physics Department, Brookhaven National Lab, Upton, US*
[2] *Department of Physics, University of Zagreb, Zagreb, Croatia*
[3] *Institut für Theoretische Physik II, Ruhr-University Bochum, Bochum, Germany*

Coming soon...

Abstract

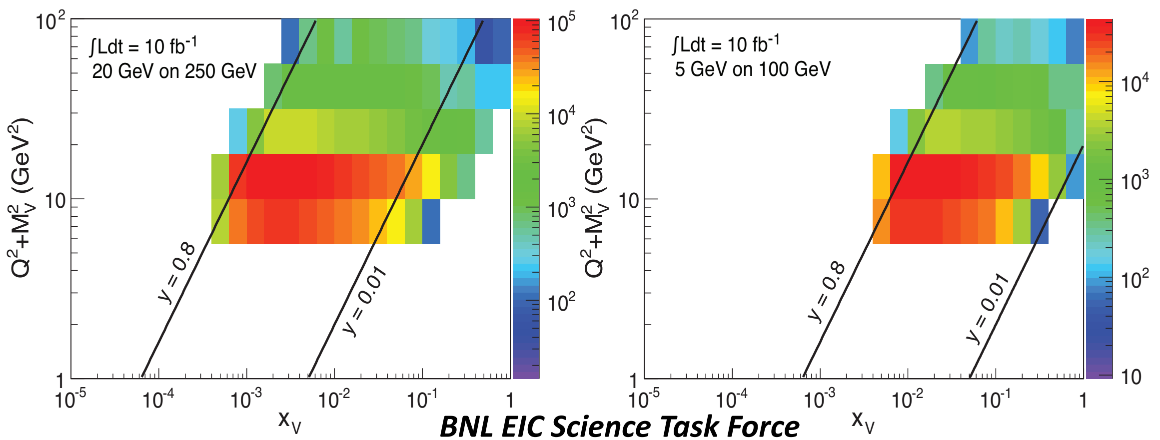
We simulate deeply virtual Compton scattering at a proposed electron-ion-collider and explore the possible impact of such measurements for the phenomenological access of generalized parton distributions. In particular we give emphasize to the transverse distribution of sea quarks and gluons and show that such measurements will provide information on the angular momentum sum rule.

J/ψ



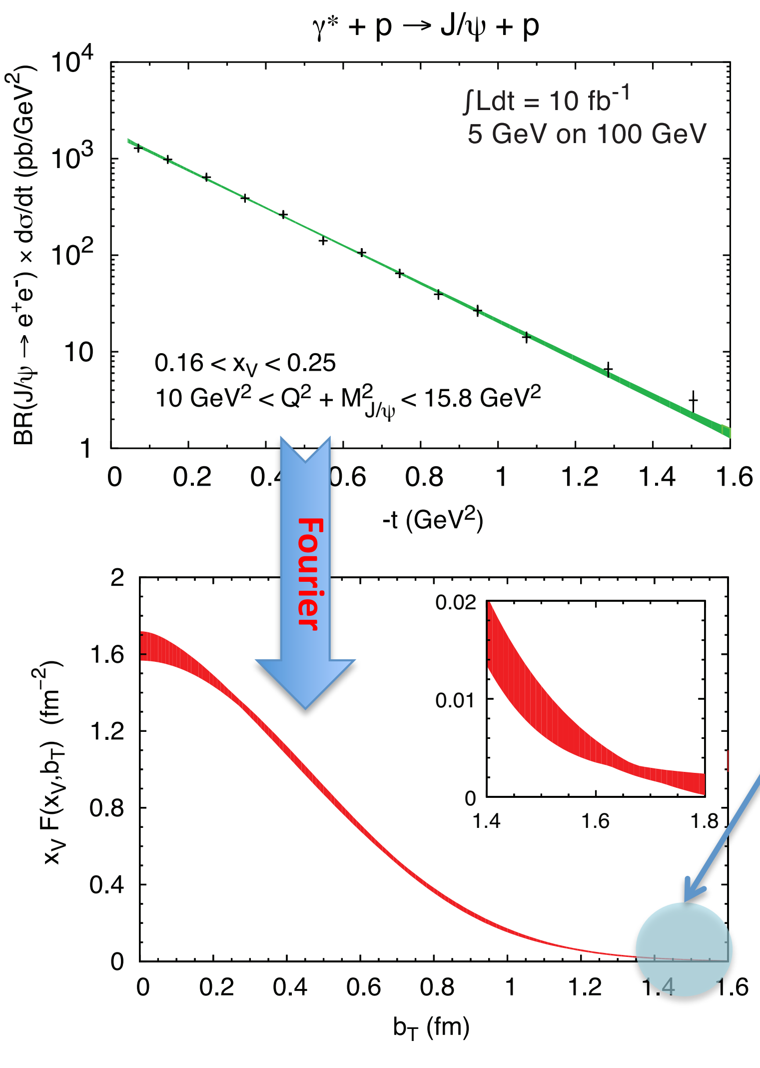
γ*p -> J/ψ p

- pseudo-data generated using a version of Pythia tuned to J/ψ data from HERA
- wave function uncert. (non-relativistic approximation)
- mass provides hard scale
  - Sensitive to gluons
  - Both photo- and electro-production can be computed



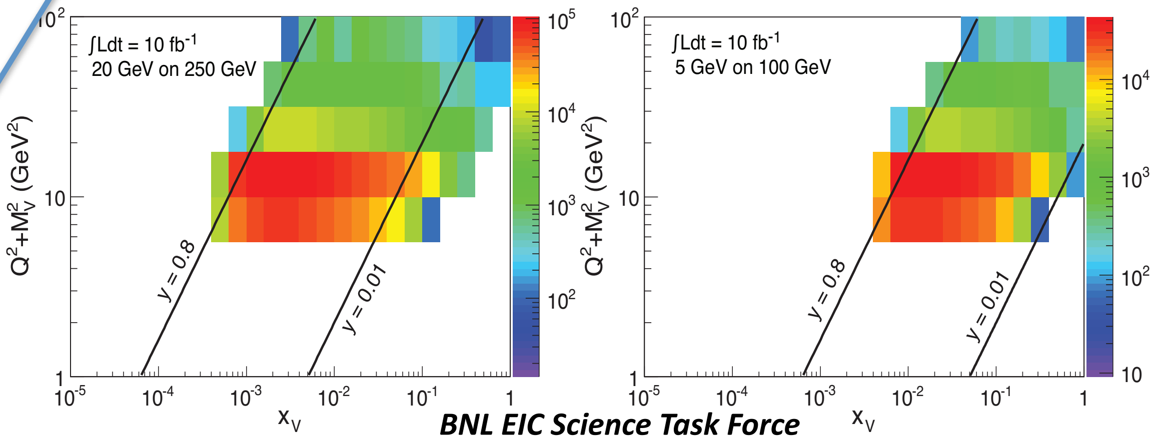
BNL EIC Science Task Force

J/ψ



$\gamma^*p \to J/\psi\ p$

- pseudo-data generated using a version of Pythia tuned to J/ψ data from HERA
- wave function uncert. (non-relativistic approximation)
- mass provides hard scale
  - Sensitive to gluons
  - Both photo- and electro-production can be computed



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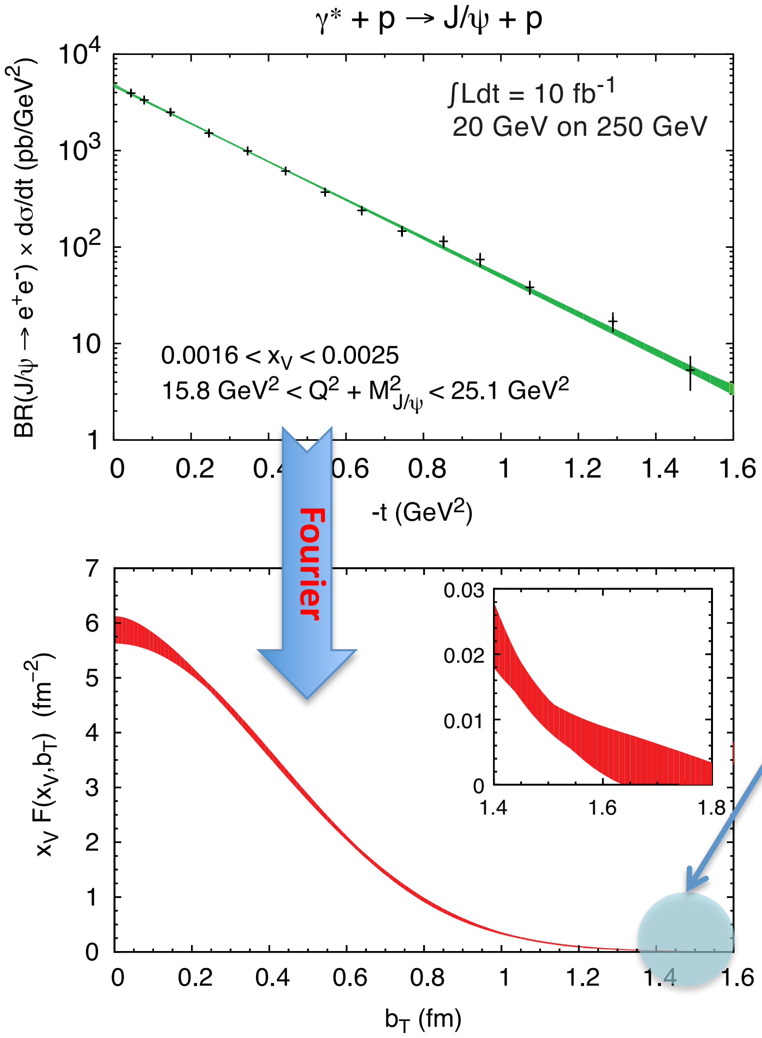

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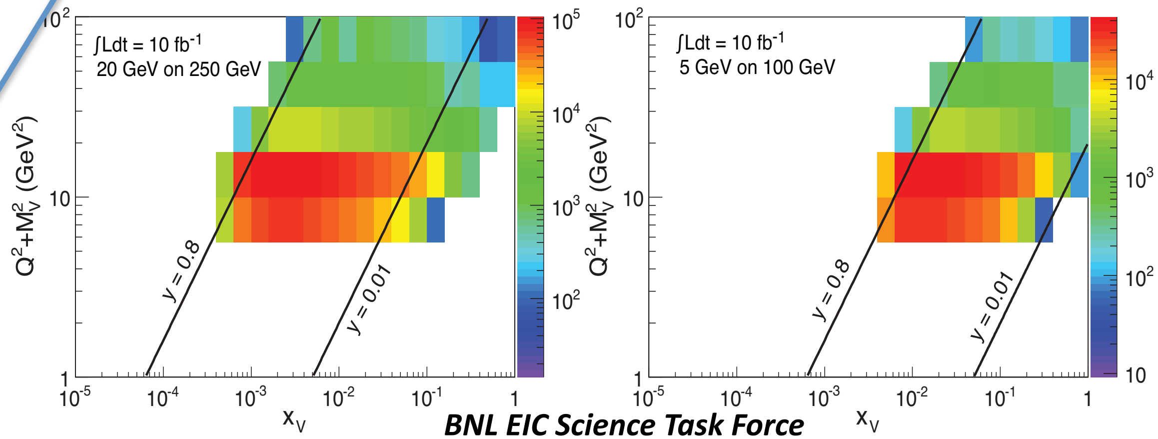

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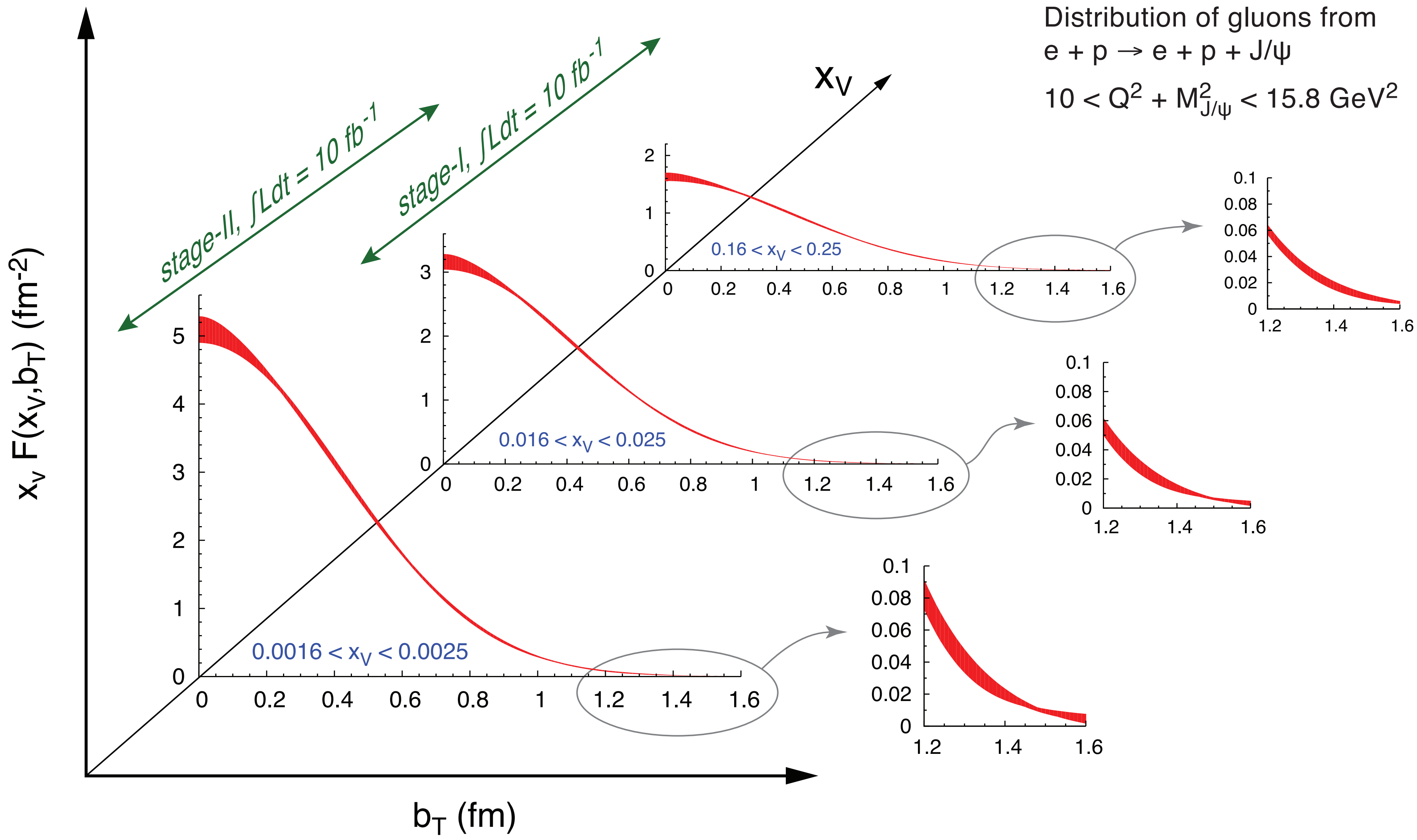
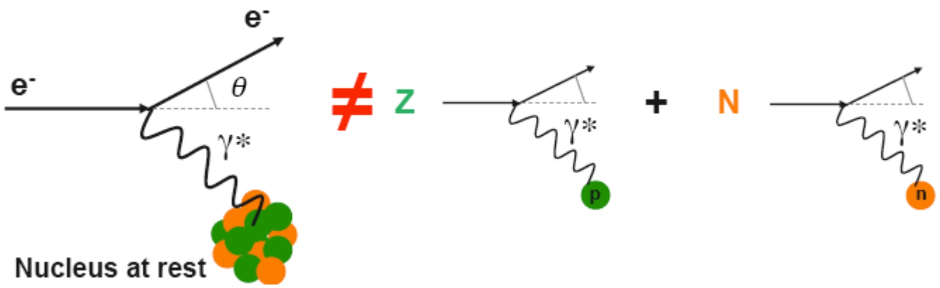


Distribution of gluons from
$e + p \to e + p + J/\psi$

$10 < Q^2 + M^2_{J/\psi} < 15.8\ \text{GeV}^2$

GPDs on nuclear targets

- How does the nuclear environment modify parton-parton correlations?
- How do nucleon properties change in the nuclear medium?

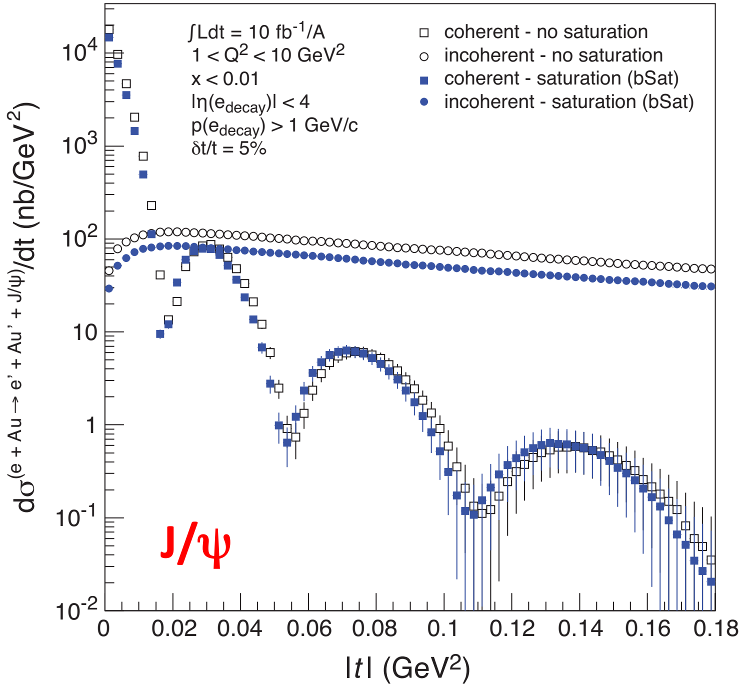


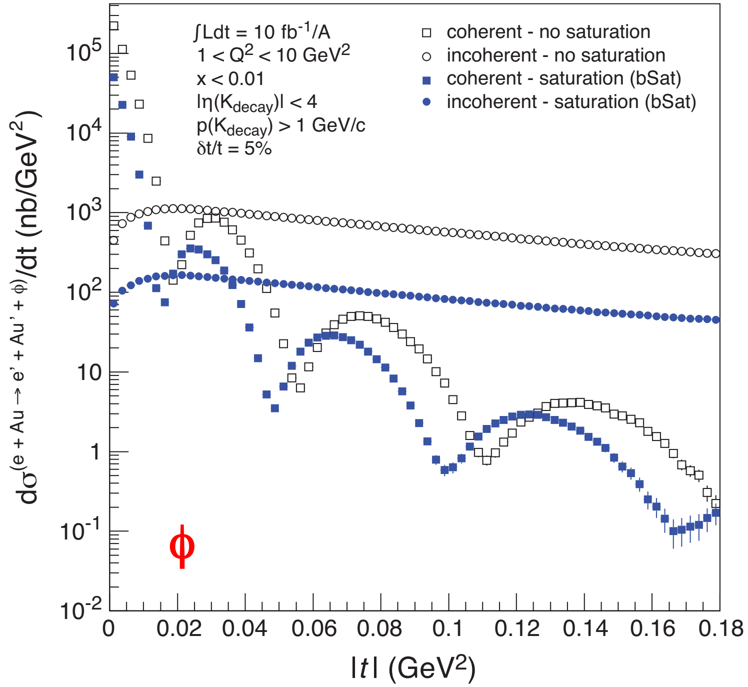
Nuclear GPDs ≠ GPDs of free nucleon

- Diffraction in e+p:
  - coherent ⇔ p intact
  - incoherent ⇔ breakup of p
  - 15% of all events at HERA
- Diffraction in e+A:
  - coherent diffraction (nuclei intact)
  - breakup into nucleons (nucleons intact)
  - incoherent diffraction
  - Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%

GPDs on nuclear targets

Exclusive VMP in e+A





- **Low-t: coherent diffraction dominates - gluon density**
- **High-t: incoherent diffraction dominates - gluon correlations**

Important: need good breakup detection efficiency to discriminate between the two scenarios

- **Coherent events identified by vetoing nuclear break-up → measure emitted neutrons in a ZDC**
- **rapidity gap sufficient to identify coherent events**

Summary

- **A lot of experience carried over from HERA**
- **DVCS can be used to drive the requirements for a dedicated new detector**
- **Simulation shows how an EIC can much improve our knowledge of GPDs**
- **A fine binning of x-sec and symmetries will be possible, uncertainties mostly dominated by systematics**
- **Large potential for an accurate 2+1D imaging of the polarized and unpolarized quarks and gluons inside the hadrons (and nuclei!)**

Summary

- A lot of experience carried over from HERA
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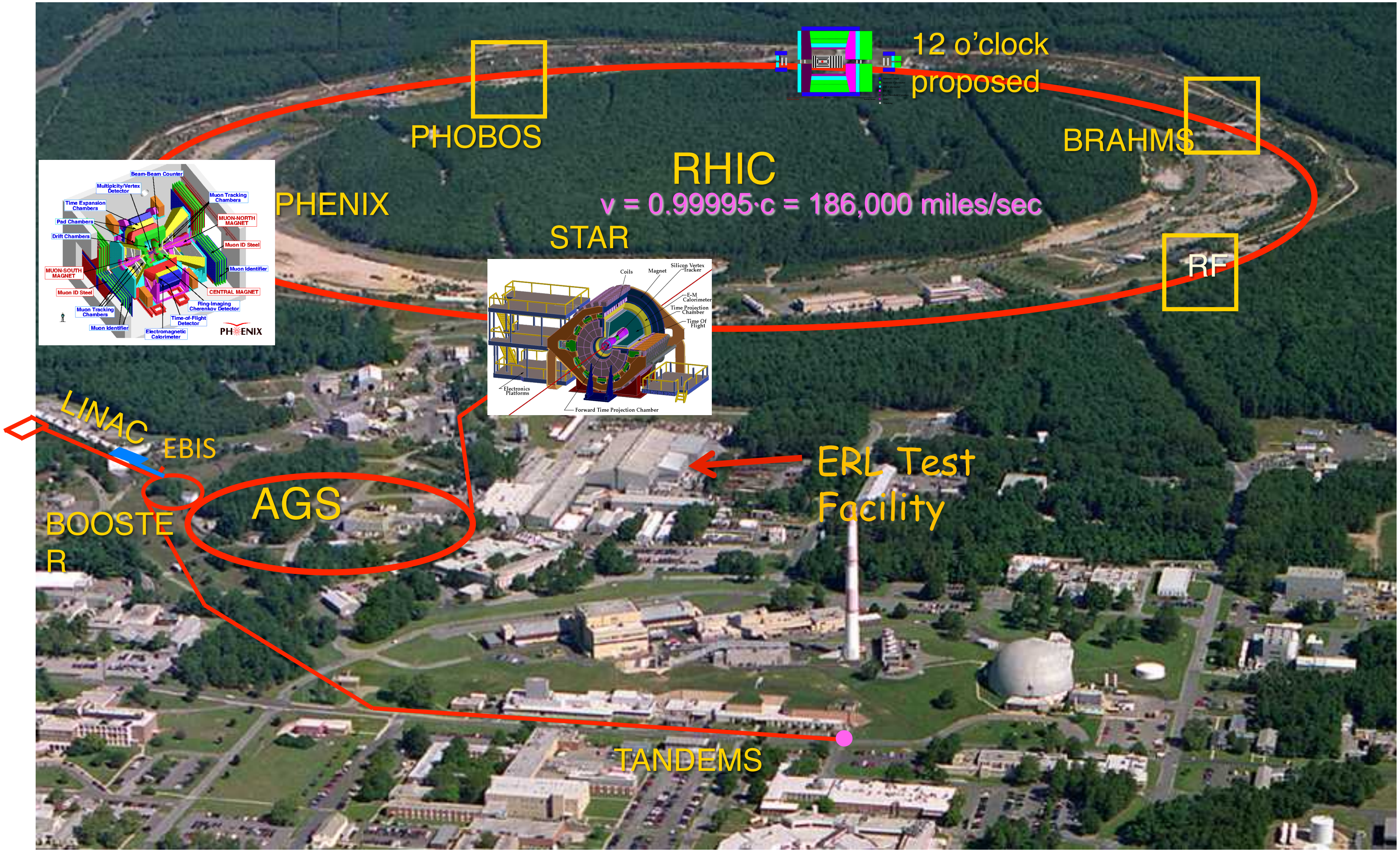
Brookhaven National Lab - EIC Science Task Force
People: Elke Aschenauer, Thomas Ullrich, Thomas Burton, Ramiro Debbe, Jamie Dunlop, Salvatore Fazio, Wlodek Guryn, Matt Lamont, J. H. Lee, Dieter Mueller, Hubert Spiesberger, Marco Stratmann, Tobias Toll, Liang Zheng
Working groups: **ep, eA, detector and machine design**
Web-page: https://wiki.bnl.gov/eic/index.php/Main_Page

Back up

The RHIC site @ BNL



(2+1)-D imaging of the proton

Longitudinal momentum & helicity distributions

transverse charge & current densities

$\int d^2 b_T$ → $f(x, k_T)$

$\int d^2 k_T$ → $f(x, b_T)$

Fourier trf. $b_T \leftrightarrow \Delta$ → $H(x,0,t)$, $t = -\Delta^2$

$\xi = 0$: $H(x,\xi,t)$ → $H(x,0,t)$

$f(x, k_T)$
transverse momentum distributions (TMDs)
semi–inclusive processes

$f(x, b_T)$
impact parameter distributions

$H(x,\xi,t)$
generalized parton distributions (GPDs)
exclusive processes

$\int d^2 k_T$ ($f(x,k_T)$ → $f(x)$)

$\int d^2 b_T$ ($f(x,b_T)$ → $f(x)$)

$\int dx$ ($H(x,0,t)$ → $F_1(t)$)

$\int dx x^{n-1}$ ($H(x,\xi,t)$ → $A_{n,0}(t) + 4\xi A_{n,2}(t) + \ldots$)

$f(x)$
parton densities
inclusive and semi–inclusive processes

$F_1(t)$
form factors
elastic scattering

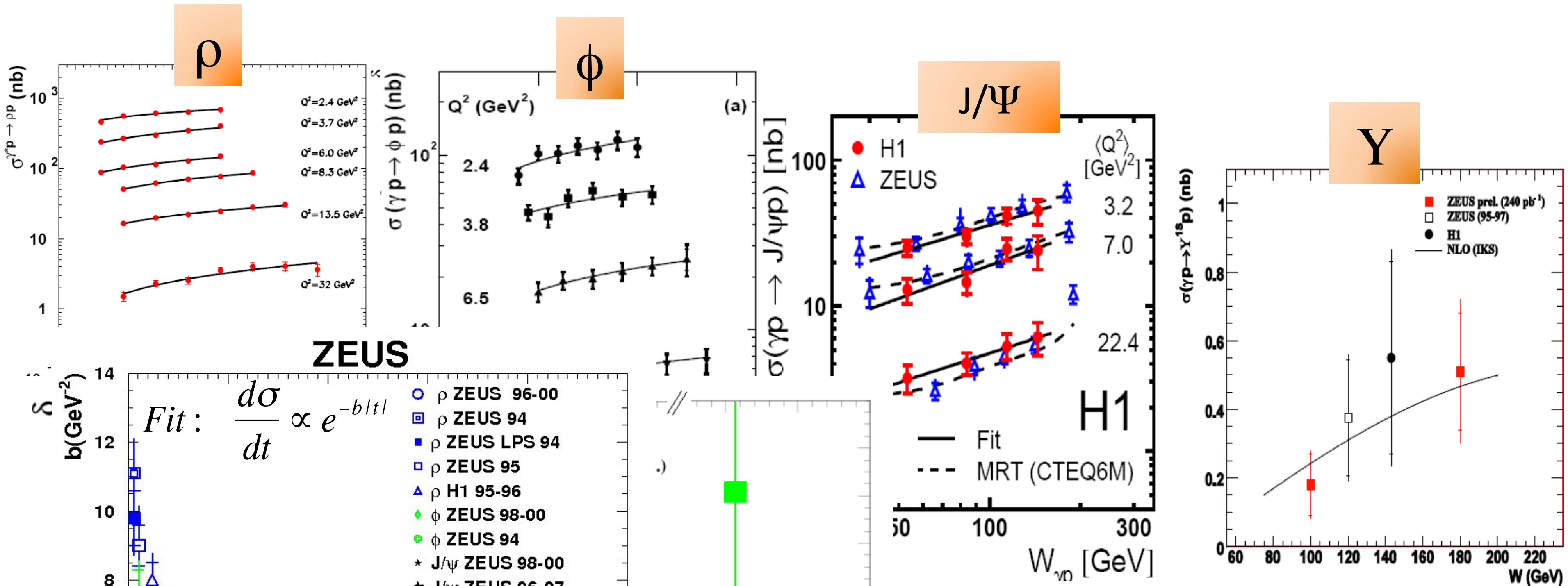
$A_{n,0}(t) + 4\xi A_{n,2}(t) + \ldots.$
generalized form factors
lattice calculations

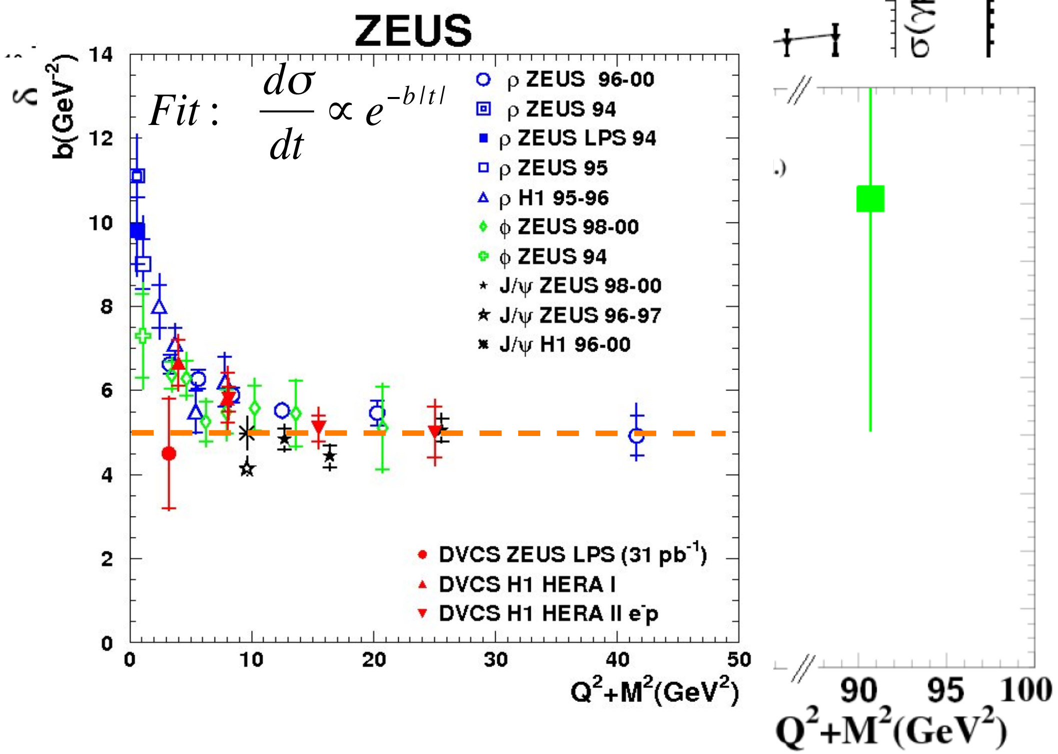
Wigner Distribution
$W(x, r, k_t)$

3D picture in coordinate space
generalized parton distributions
→ exclusive reaction like DVCS and VMP

Vector Meson Production

W & t dependences: probe transition from soft → hard regime





$\sigma \sim W^{\delta}$

$\sigma \sim e^{-b|t|}$

- steep energy dependence of σ in presence of the hard scale
- universality of b-slope parameter: point-like configurations dominate

MC simulation

Written by E. Perez, L Schoeffel, L. Favart [arXiv:hep-ph/0411389v1]

The code MILOU is Based on a GPDs convolution by:
A. Freund and M. McDermott [All ref.s in: http://durpdg.dur.ac.uk/hepdata/dvcs.html]

- ✓GPDs, evolved at NLO by an indipendent code which provides tables of CFF
  - at LO, the CFFs are just a convolution of GPDs:

$$\mathcal{H}(\xi,Q^2,t)=\sum_{u,d,s}\int_{-1}^{1}\left[\frac{e_i^2}{1-x/\xi-i\varepsilon}\pm\{\xi\to-\xi\}\right]H_i\left(x,\xi,Q^2,t\right)dx$$

- ✓provide the real and imaginary parts of Compton form factors (CFFs), used to calculate cross sections for DVCS and DVCS-BH interference.

$$\frac{d\sigma}{dxdyd|t|d\phi d\varphi}=\frac{\alpha^3 x_B y}{16\pi^2 Q^2\sqrt{1+\varepsilon^2}}\left|\frac{\mathcal{I}}{e^3}\right|$$

$$\phi=\phi_N-\phi_l$$

$$\varphi=\Phi_T-\phi_N$$

$$\varepsilon\equiv 2x\frac{m_N}{Q}$$

$$|\mathcal{I}_{\mathcal{BH}}|^2=\frac{e^6}{x^2y^2(1+\varepsilon^2)^2\Delta^2\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left\{c_0^{BH}+\sum_{n=1}^{2}c_n^{BH}\cos(n\phi)+s_1^{BH}\sin(\phi)\right\}$$

$$|\mathcal{I}_{\mathcal{DVCS}}|^2=\frac{e^6}{y^2Q^2}\left\{c_0^{DVCS}+\sum_{n=1}^{2}\left[c_n^{DVCS}\cos(n\phi)+s_n^{DVCS}\sin(n\phi)\right]\right\}$$

$$|\mathcal{I}|^2=\frac{\pm e^6}{xy^3\Delta^2\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left\{c_0^{I}+\sum_{n=1}^{3}c_n^{I}\cos(n\phi)+s_1^{I}\sin(\phi)\right\}$$

- ✓ $\frac{d\sigma}{d|t|}=\exp\left(B\left(Q^2\right)t\right)$ -> The B slope is allowed to be costant or to vary with Q^2:
- ✓Proton dissociation (*ep* → *e* *γ* *Y*) can be included
- ✓Other non-GPD based models are implemented like FFS, DD

Data simulation & selection

Acceptance criteria

- for Roman pots: $0.03 < |t| < 0.88\ GeV^2$
- for |t| > 1GeV2 detect recoil proton in main detector
- $0.01 < y < 0.85\ GeV^2$
- $\eta < 5$

➢ BH rejection criteria (applied to x-sec. measurements)

- $y < 0.6$
- $(\theta el-\theta\gamma) > 0$
- $Eel>1GeV^2$; $Eel>1GeV^2$

➢ Events smeared for expected resolution in t, Q2, x

➢ Systematic uncertainty assumed to be ~5% (having in mind experience from HERA)

➢ Overall systematic uncertainty from luminosity measurement not taken into account

The code MILOU by E. Perez, L Schoeffel, L. Favart [arXiv:hep-ph/0411389v1] is Based on a GPDs convolution by: A. Freund and M. McDermott [http://durpdg.dur.ac.uk/hepdata/dvcs.html]

$0.01 < |t| < 0.85\ GeV^2$

(Low-|t| sample)

- **Very high statistics**
- **Systematics will dominate!**
- **Within Roman pots acceptance**

$1.0 < |t| < 1.5\ GeV^2$

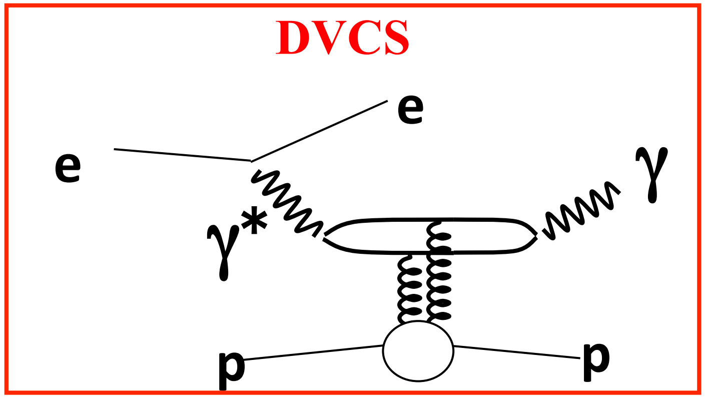
(Large-|t| sample)

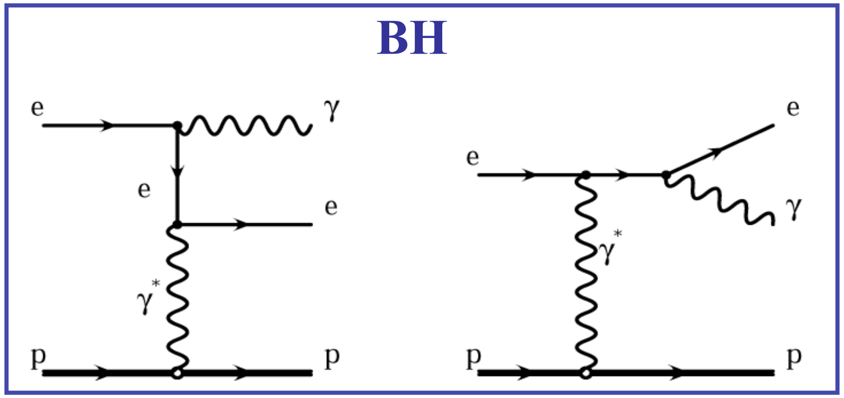
- **Xsec goes down exponentially**
- **requires a year of data taking**
- **Main detector can be used in measuring |t|**

Stage 1: 5 X 100 GeV → **~10 fb^{-1} (~ 10 months)**

Stage 2: 20 X 250 GeV → **~100 fb^{-1} (~ 1 year)**

DVCS - BH





$$\frac{d\sigma}{dxdy\,d|t|\,d\phi d\varphi} \propto \left|\mathcal{T}_{\mathcal{DVCS}}\right|^2 + \left|\mathcal{T}_{\mathcal{BH}}\right|^2 + \left|\mathcal{T}_{int}\right|^2$$

DVCS cross section: BH becomes background -> must be removed

Uncertainty on proton form factor → **uncertainty on BH xsec ~ 3% (at LO)**

Asymmetry measurement -> BH is the vehicle to study interference term

θ_γ vs E_γ

10 X 100